National Cave and Karst Research Institute 400-1 Cascades Avenue Carlsbad, New Mexico 88220 NCKRI SYMPOSIUM 2 Proceedings of the 13th Multidisciplary Conference and the Engineering and Environmenal Impacts of Karst on Sinkholes

2013

NCKRI SYMPOSIUM 2 Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst

Edited by: Lewis Land, Daniel H. Doctor, and J. Brad Stephenson



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NATIONAL CAVE AND KARST RESEARCH INSTITUTE Symposium 2

Sinkholes and the engineering and environmental impacts of karst

PROCEEDINGS OF THE THIRTEENTH MULTIDISCIPLINARY CONFERENCE

May 6 through 10, 2013 Carlsbad, New Mexico

EDITORS:

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Cover Photo:

Aerial view of the JWS sinkhole, Eddy Co., New Mexico, about six weeks after initial collapse. Photo compliments of the National Cave and Karst Research Institute.

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FOREWORD

Welcome to the Thirteenth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst in sunny Carlsbad, New Mexico. This will be the farthest west the Sinkhole Conference, as it is informally known, has met since its inception in 1984. The setting will provide conference participants with a unique opportunity to view karst phenomena such as gypsum cenotes that are uncommon outside the southwestern United States, and world-class caves and karst features that occur (for better or worse) within and adjacent to giant oil fields of the Permian Basin region.

In 2011 the National Cave and Karst Research Institute (NCKRI) assumed responsibility for hosting the Sinkhole Conference series. NCKRI, a non-profit organization dedicated to pure and applied research on caves, karst phenomena, and karst hydrology is well-positioned to assume a leadership role in organizing and hosting the conference. Several of the staff of NCKRI have a long history of participation in past Sinkhole Conferences, and we look forward to supporting and hosting future meetings in other areas of the United States and abroad. The fourteenth conference will be held in Minneapolis, Minnesota in 2015, and discussion has begun on the possibility of an international setting for a future conference.

We wish to dedicate this year's proceedings volume to the memory of Barry Beck, who died in 2011. Barry initiated the Sinkhole Conference series in 1984 and was instrumental in maintaining the series of meetings over the years through several sponsors. Although his energy and enthusiasm will be greatly missed by future conference organizers, we are honored to carry Barry's legacy into the future.

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SPELEOLOGICAL, HYDROGEOLOGICAL AND ENGINEERING GEOLOGICAL CHALLENGES OF TUNNELING IN KARST AREAS

Dr. Mladen Garašic

University of Zagreb, Croatia

In the Classical Dinaric Karst of Croatia, over 11,500 caves have been explored so far, more than 1,000 of which were discovered during construction works. Caves discovered on the construction sites of highways lacked natural entrances on the surface. Over the past 20 years they have been systematically investigated and remediated to allow completion of the roads. Some special examples will be presented during the lecture, such as the large hall in the Vrata Tunnel of the Zagreb -Rijeka Highway, and caves in Croatia's longest tunnels. Due to the size, shape, position, and hydrogeological parameters of the cave within the karst system, it was necessary to design and construct a special bridge through the cave in the Vrata Tunnel. The cave's vaulted ceiling had to be reinforced and stabilized. This presentation will include video and photos of the most interesting karst and cave locations in Dinaric Karst.

Biography

Mladen Garašic, PhD. Geology, Hydrogeology, and Geological Engineering. Born in Zagreb, Croatia, in 1951, Dr. Garašic graduated in geology and karst hydrogeology in 1977, master of science 1981, and doctorate in geosciences and geological engineering in 1986. He is a scientist, and a professor of geology, karst hydrogeology, applied geology, engineering geology and speleology at the University of Zagreb, and has authored more than 330 scientific and professional papers. He serves as a committee member for the Croatian Academy of Science and Arts, UNESCO World Heritage Team for the Dinaric Karst, International Association of Hydrogeologists, and International Association for Engineering Geology and the Environment.

Dr. Garašic started skiing in 1955 and won the Junior Skiing competition of Croatia in 1963. He has been a member of the Croatian Mountaineering Association since 1955 and was awarded by the Association in 1969 and 1981. He started caving in 1963 and is the founder and president of several caving clubs in Croatia. He served as first president of the Croatian Speleological Federation from 1990 to 2010 and is a life member of the U.S. National Speleological Society. Since 1993, he has served as Croatia's delegate to the International Union of Speleology and to the European Speleological Federation beginning in 2009.

Dr. Garašic has conducted research in, and explored and visited nearly 5,000 caves in 64 countries. He has led many speleological expeditions in the longest and deepest caves in Croatia, Europe, and the world. He has also studies about 1,000 caves without natural entrances, discovered by tunnels and quarries, and evaluated their hydrogeology and engineering geology.

KEYNOTE SPEAKER

NATURAL AND ANTHROPOGENIC SINKHOLES: FROM IDENTIFICATION, TO SURVEYING, STUDYING AND MODELING A SUBTLE HAZARD

Mario Parise

National Research Council of Italy, Institute of Research for the Hydrogeological Protection

Sinkholes are the most common hazard in karst, being related to the presence of natural caves, and to their interaction with the ground surface. In the last decades, however, the study of sinkholes widened well beyond the boundaries of karst, including situations where cavities produced by man in different epochs and for different purposes interact in some way with the built-up environment, and represent a likely threat to the society. As a matter of fact, several urban areas in many countries worldwide have been recently affected by sinkhole occurrence which caused severe damage; sinkholes in Guatemala City, and other events in Italy, Germany and Turkey are only some of the many that characterize the last several years.

In terms of civil protection issues, the topic has become of high interest in Italy, and much work has been devoted to it at CNR-IRPI. This presentation briefly describes the activities carried out, as they concern both natural and anthropogenic sinkholes, and to share the experiences so far developed. These latter cover all the phases of sinkhole analysis: from the identification of the sinkholeprone areas, to surveying the underground environment (by combining speleological techniques and modern technologies in order to get reliable and precise surveys), to recognizing the type of rock failures and characterizing the rock mass in terms of mechanical properties, to eventually modeling the case studies through numerical codes in order to forecast the likely evolution of underground failures, their upward propagation, and evaluating the possibility of sinkhole occurrence at the ground surface. A particular focus will be given to historical research, and its use in identifying ancient and/ or buried caves, as the first step in the assessment of the sinkhole susceptibility and hazard. All of this will be illustrated through a number of case studies in southern Italy, dealing with natural karst caves and anthropogenic cavities as well. The final part of the presentation will

also cover some issues related to land-use problems in sinkhole-prone areas, and the utilization of the outcomes from sinkhole studies in civil protection programs at the local and national level, aimed at safeguarding and protecting private and public properties and the local populations.

Biography

After graduating with honors in Geology in 1988 at the Faculty of Sciences of the University of Naples, Mr. Parise received grants from the National Research Council of Italy and spent several periods working in cooperation with the U.S. Geological Survey at Golden, Colorado, and the University of South Florida at Tampa, Florida. Since 1994 he has worked as a Research Geologist at the National Research Council, Institute of Research for Hydrogeological Protection (CNR-IRPI) in Bari, Italy. He has organized and convened several international workshops and conferences on the topics of karst, karst hazards, and slope movements (European Geosciences Union Assemblies, Geological Society of America Meetings, Italian Forums of Earth Sciences), and is the scientist responsible for several projects between CNR-IRPI and different public administrations and private companies.

Since 1990, Mr. Parise has developed research mainly into the geological and geomorphological analysis of slope movements. Much of his research deals with the identification of areas susceptible to different types of slope movement (debris flows, deep-seated gravitational slope deformations, mass wasting processes, etc.) by means of stereoscopic interpretations of aerial photographs and field surveys. Particular focus is given to multi-temporal analyses, aimed at understanding the likely evolution of slopes, even in relationship with anthropogenic activities, and/or as a consequence of specific triggering events (rainstorm, earthquakes, etc.). For several sites in southern Italy, he has created a framework of the influence of weathering in the predisposition of slope movements. He has also contributed to the analysis of rapid landslides (debris avalanches, rock avalanches) in different geological settings in Italy and abroad, and to studying the occurrence of debris flows and erosional processes in areas recently affected by wildfires.

He began caving in 1998 and since 2002 he also works in the field of karst research, focusing on the evaluation of natural and anthropogenic hazards that occur in karst territories, with particular regard to sinkholes related to both natural caves and man-made cavities. He is the author of over 100 papers published in international journals and proceedings of international conferences. He has given several presentations in international symposia and workshops. Mr. Parise has guest edited 10 special issues for ISI international journals, published two books with the Geological Society of London, and reviews papers for several international journals.

TECTONIC INFLUENCES ON PETROLEUM MIGRATION AND SPELEOGENESIS IN THE GUADALUPE MOUNTAINS, NEW MEXICO AND TEXAS

Harvey R. DuChene

Vecta Oil and Gas, LP

Sulfuric acid speleogenesis in the Guadalupe Mountains is a consequence of the rise of the Alvarado ridge and subsequent opening of the Rio Grande Rift during Cenozoic time. Uplands of the late Laramide ($\sim 38 - 35$ Ma) Alvarado Ridge provided an immense recharge area that supplied water to aquifers draining eastward to the Permian basin. Evidence for east-directed hydrodynamic flow is the displacement, microbial degradation and subsequent recharging of hydrocarbons in large structural and stratigraphic traps in Artesia Group (Permian, Guadalupian) reservoirs in southeast New Mexico and adjacent west Texas. Prior to, or during the early stages of the development of the Rio Grande Rift, hydrostatic head in the Capitan aquifer caused water to flow eastward through Artesia Group strata toward the Permian basin. Some of this water moved upward along fractures to artesian springs in the area of the Guadalupe Mountains. This resulted in solutional enlargement of fractures and development of early stage caves. Extensional faulting since 29 Ma fragmented the east flank of the ridge, progressively reducing the size of the upland recharge area and reducing hydrostatic head. Fresh water influx introduced microbes into Artesia Group (Permian, Guadalupian) reservoirs causing biodegradation of petroleum and generating copious H₂S.The water table within the Guadalupe Mountains began to fall 14-12 Ma in response to erosion and tectonism. During this time, oxygen-rich meteoric water mixed with H₂S water to form sulfuric acid, which enlarged passages and galleries at the water table. Tectonic spasms related to the opening of the Rio Grande Rift caused abrupt drops in the water table, shifting the locus of sulfuric acid

dissolution eastward and downward. Cave levels formed by sulfuric acid record the position of the water table at a given time, and the elevation difference between levels may correlate with episodes of Rio Grande Rift tectonism since 12 Ma.

Biography

Harvey DuChene is a graduate of the University of New Mexico, earning B.A. (1968) and M.S. (1973) degrees in geology. He has 39 years of experience as a petroleum geologist, working for Amoco Production Company, Davis Oil, Axem Resources and others. He currently is a limited partner in Vecta Oil and Gas, LP, an oil and gas exploration and production company headquartered in Dallas, Texas. His primary area of expertise is petroleum exploration in basins of the Rocky Mountain province and west Texas, with additional experience in the midcontinent, Appalachian basin and offshore West Africa.

Harvey has also more than 30 years studying the speleogenesis of hypogenic caves, particularly those formed by sulfuric acid. He is interested in the connection between the evolution of hypogenic cave systems and the tectonic and geologic history of regions.

Harvey is a member of the Geological Society of America, American Association of Petroleum Geologists, American Geological Institute, Rocky Mountain Association of Geologists, New Mexico Geological Society, West Texas Geological Association and Karst Waters Institute, and he is a Fellow of the National Speleological Society.

KEYNOTE SPEAKER

WHEN THE CARBONATE PLUMBING GOES BAD: SINKHOLES, THE HYDRA, AND THE GENERAL PUBLIC

William Kochanov

Pennsylvania Department of Conservation and Natural Resources

In 1985, a program was initiated by the Pennsylvania Geological Survey to inventory (catalog) existing sinkholes and to map areas of potential sinkhole development. The program was developed to provide general background information for the initial stages of site investigations, aid in sinkhole remediation efforts, and serve as a tool for developing regional land-use planning strategies. Although the methods of data collection and distribution have evolved over the past 25 years, it has been interesting to note that the practicing professional continually has had to refine the means of sorting and sifting data much like that of a forensic specialist; each investigator having their own special challenges as the clues for remediation often lie hidden beneath the veneer of urbanization, are squirreled away in files of the local Historical Society or are muted for fear of liability. Bill will take you on a savage journey through the karstlands of Pennsylvania to marvel at some of its many wonders, examine yawning portals to the underworld, grapple with the paradox of the cultural hydra, and the ultimate in trepidation, entering the lair of the general public.

Biography

William (Bill) Kochanov (pronounced KO-CHAN'-OFF) is a Senior Geologist with the Pennsylvania Department of Conservation and Natural Resources, Bureau of Topographic and Geologic Survey, Geologic Mapping Division. Since 1985, he has been actively mapping geologically hazardous areas within the limestone regions of Pennsylvania and maintains the Bureau's sinkhole database. He has also conducted bedrock mapping projects spanning much of the Paleozoic from Pennsylvania's northern anthracite coal field and Endless Mountains Region to the Chester Valley of southeastern Pennsylvania. Bill is most noted for authoring the series of county reports, specifically designed to characterize karst surface features, their distribution, and their relation to physiographic setting. He is strongly involved with the Survey's outreach programs; translating the geology of Pennsylvania for, as Joe Fischer puts it, "the greater unwashed." Bill lives in the suburbs of Harrisburg with his wife Jane and children, Natalie and Alex, close to the forests of Stony Creek where he spends many hours tracking down the elusive edibles of the mushroom world.

TOWARDS A KARST ASSESSMENT STANDARD PRACTICE

Robert K. Denton Jr., CPG, CPSS

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Abstract

The assessment of karst conditions and putative karst geohazards prior to residential and commercial development is currently in its infancy, from a scientific aspect. Borrowing from the medical lexicon, most karst features at proposed building sites are dealt with using an approach wherein the "symptoms and conditions" are treated (e.g. sinkhole remediation), often only after site development activities have commenced. If karst hazards are suspected, roadways, foundations and specific at-risk areas may be investigated using various geophysical methods; however the results of these investigations require specialized knowledge to be interpreted and understood. Thus stakeholders without geological training may find the investigator's results indecipherable, often leading to unnecessary and expensive supplemental studies, the need for which is entirely based on the non-technical stakeholder's faith in the investigator's judgment.

In contrast, a recent trend among consulting firms is to attach cursory karst "assessments" to due diligence study reports, particularly Phase I Environmental Site Assessments. These combined assessments are often performed by individuals who are inexperienced in geology, often without any specific training in karst geology. Not unexpectedly, this can lead to numerous mistakes, errors, and oversights. More troubling, these studies often report a lack of karst risks at the site under study, a result that the stakeholders may initially embrace, but which later can result in substantial financial loss and/or significant threats to human health and the environment.

To address these concerns, we propose a proactive, "preventative" standard practice for karst assessments. Ideally, this proactive approach will help to delineate potential karst hazards so that they can be avoided, managed, or corrected by remediation. Requirements for investigators, a proposed scope of services, fieldwork and data review checklist, and a template for a follow-up karst management plan are presented. It is our hope that if carried out and reported accurately, the proposed assessments should allow even a nontechnical stakeholder to make informed decisions regarding the relative risk of karst geohazards, the need for further studies, and potential corrective actions that site development may entail.

Introduction and Background

The study of karst features, in particular karst springs and groundwater stretches back into earliest written human history. One of the first formal descriptions of caves and their hydrography was written in 221 B.C.E. in China, and the solution process of carbonate rocks was described accurately by the Roman Philosopher Seneca (4 B.C.E. – 65 C.E.). Commentary by naturalists and philosophers on karst features and hydrology continued in both Europe and Asia through the subsequent centuries and entered into the era of systematic geomorphological investigation in the 19th century (LaMoreaux and LaMoreaux, 1998).

Not surprisingly, in regions where much of the land surface was underlain by soluble bedrock and prone to the development of karst terrain, karst studies were advanced by the interests of regional politics (Zotl, 1974). One such area was central Europe, where the Austro-Hungarian Empire had acquired extensive tracts of karst lands. The need to ensure that water supplies were adequately developed and infrastructure was protected drove these studies forward, and arguably the Austrian studies could be considered the first examination of karst as a geohazard, in particular Cvijic's 1893 monograph Das Karstphanomen. Nevertheless, the majority of interest in karst remained of a purely scientific nature, and there was little emphasis on assessing the environmental and economic impacts of human development in karst terrains until the latter half of the 20th Century (LaMoreaux, et al, 1975; Moser and Hyde, 1974; Rauch and Werner, 1974).

An increased sense of environmental awareness, coupled with increasing residential and commercial development in karst terrains during the 1970s and 1980s led to increased interest in the characterization and mitigation of karst hazards and environmental impacts. The Center for Cave and Karst Studies at Western Kentucky University was one of the first programs in the United States specifically created to deal with karst, from both scientific and engineering aspects. At a national level, the importance of karst studies was heralded by the creation of the National Cave and Karst Research Institute (NCKRI).



Figure 1. A Virginia newspaper story detailing the 1992 collapse of a house in the Shenandoah Valley into a sinkhole.

Simultaneously, local jurisdictions began to respond to karst geohazard issues on their own, driven by various incidents that brought caves and karst to the forefront of public interest. (Figure 1).

As a result of this increased public interest and concern, a series of karst model ordinances were proposed at both state and county levels across the United States (Karst Portal, 2012). Typically, these model ordinances dealt with the "what" and "where" of karst, but not the "who" and "how". Karst studies were increasingly being required by planning boards and zoning commissions as part of the studies for approval and permitting of residential and commercial development in potential karstlands, but the manner in which the studies were conducted, and the necessary qualifications of the investigators, was typically not specified.

During the last decades of the 20th century there was a veritable renaissance in academic studies regarding

speleogenesis, karst hydrology and karst biology, yet ironically there was little attempt to advance the development of a "karst site assessment" as a standard practice. The putative process languished at the same stage of evolution as environmental site assessments prior to the creation of the specific due diligence scope of work codified in the American Society of Testing and Materials (ASTM) E1527 practice. Karst "assessments" ranged in nature from cursory sinkhole inventory and rudimentary geophysical subsurface investigation (often without any interpretation), to geologically detailed and often indecipherable "all-inclusive" investigations, none of which would assist municipal planners, regulators and/or developers in making well-informed decisions. Frequently the lack of any obvious surface karst features (e.g. sinkholes or caves) would result in a finding by the investigator(s) that there were "no karst issues" at a site. In contrast, investigators might recommend lengthy and detailed follow-up studies where none were warranted. Errors and misstatements of these sorts made karst studies misleading and essentially useless for responsible development and land planning.

Towards a Standard of Practice

In response to the polyglot of assessment schemes a movement towards a karst assessment "standard of practice" began to take form in the first decade of the 21st century. Notable examples were the Virginia Sinkhole Classification Scheme for Land Use Planning (Orndorff, et al, 2001), Kentucky Model Karst Ordinance (Currens, 2009), the Clarke County Virginia Sinkhole Ordinance (Code of Clarke County, 1997) and Karst Plan Requirements (Teetor, 2004), and Chapter 6 of the Loudoun County Virginia Facility Standards Manual – Limestone Overlay District (2010). Nevertheless, a single karst assessment standard of practice similar to the ASTM standard practice for Environmental Site Assessments (ASTM, 2005) was lacking.

Thus, what we present in this article is a proposed model standard of practice that embodies a set of basic elements that should be included in any karst site characterization. It must be emphasized that this approach is not to be considered the <u>exclusive</u> requisite elements in a karst assessment, but the essential starting points for a basic (preliminary) evaluation. Karst assessments will vary according to the needs of the user(s), the requirements embodied in local ordinances and the scope and nature of the proposed development. However, if performed

in accord with this scheme, and reported accurately, the proposed assessments should allow even a non-technical stakeholder to make informed decisions regarding the relative risk, the need for further studies, and potential corrective actions that site development may entail.

Requirements for Karst Investigators

Based on jurisdictions that have requirements for karst investigations, the recommended minimum qualification for the karst professional investigator is as follows:

A Professional Engineer (PE) with a geotechnical (civil) engineering specialty and 5-years of experience in karst geology and/or hydrology; (or)

A Certified Professional Geologist (CPG) with a minimum of 5-years experience in karst studies and engineering geology;

A statement of qualifications, signed and sealed, with supporting documentation (e.g. resume, curriculum vitae, etc.) should be part of the assessment report, including a statement specifying that the investigator meets the definition of a karst professional investigator as defined above.

It is important to understand that a P.E. license does not necessarily qualify an individual to be a karst investigator, or make recommendations regarding engineering solutions for karst geohazards. By the same token, many licensed geologists have never had any formal training or experience with engineering geology or geotechnical engineering. Specific expertise and experience dealing with karst issues is the most critical factor in designating an individual as a karst professional investigator.

An example of a well-written definition of a qualified karst investigator can be found in the Clarke County Va. Karst Plan Requirements:

Geotechnical Engineer – A Virginia registered professional engineer (PE) engaged in the practice of Geotechnical Engineering, or a Virginia Registered Professional Geologist (PG) who is engaged in the practice of engineering geology.

Although the definition of a "geotechnical engineer" is somewhat of an exaggeration in the above statement of qualifications, (i.e. an "engineer" needs to be licensed to be called such, and a licensed geologist is not an engineer although in the Clarke County regulation they are defined as such), the intent is admirable. Where the Berryville, Clarke County Va. statute falls short is not requiring specific experience in karst. Thus, a PE or CPG with little or no experience in karst geology could theoretically sign and seal an investigation, within which recommendations have been made that could be poorly informed at best, or lead to disastrous consequences at worst.

Finally, it cannot be emphasized more that karst is not a uniform geomorphological process, and varies considerably from region to region. A geologist or engineer with experience in the relatively weak and collapse-prone Tertiary carbonates of Florida may not be familiar with issues affecting the stronger and more competent Paleozoic carbonates of the Appalachian region, or the Mesozoic carbonates of the Texas plateaus. Thus, it is important that an investigator have specific experience in the regional karst where the assessment is being conducted.

Definitions and Terminology

The lexicon of karst literature is among the most varied and complex of the earth sciences, due to much of the seminal work being carried out in non-English speaking countries. Thus, myriad terms are often used for the same structure (e.g. swallet, insurgence, sinking stream, ponor, swallow hole, perte de riviere, all of which refer to the same feature). As much of karst description is typological in nature, the specific terms that are used to describe a feature must be consistent and understandable to both a professional reviewer and a non-technical user. Thus, each assessment should include at least a brief glossary wherein the specialized terms being used are explained and clearly defined. The source reference for this glossary should be the publication "A Lexicon of Cave and Karst Terminology with Special Reference to Environmental Karst Hydrology" published by the U.S. Environmental Protection Agency (Field, 2002).

Recommended Scope of Services

The geologist or other qualified individual shall undertake an inspection of the site area and prepare an investigation report which shall include (but not be limited to) the following elements:

a. Site description and terrain analysis;

- b. Description of published soils and underlying bedrock and comparison to onsite observations;
- c. Delineation of major surface drainages and water features;
- d. Location and delineation of major karst features and drainages including, but not limited to: sinkholes (both active and incipient), caves, insurgences (swallow sinkholes), resurgences (springs), losing streams, and potential for "covered" karst (i.e. sinkholes lying beneath soils cover);
- e. Inferred locations of shallow bedrock (based on evidence from rock outcrops)

The assessment should include a summary of findings, with any recommendations made by the investigator for additional studies which may include electrical resistivity studies, seismic studies, subsurface borings, or any other appropriate method to determine if the proposed development may have negative impact on human health, safety, property or the environment.

The findings should be summarized as follows:

No evidence of karst features – If the investigator finds that the site is not underlain by soluble bedrock, or there is no evidence of karst features (including "covered" karst or pinnacled bedrock), they shall so indicate.

Evidence of karst features – In cases where the investigator finds evidence of karst features which would be impacted by development, detailed subsurface investigations shall be required within a 100-foot radius of all areas where karst features were identified, and along any linear trend of three or more aligned features. For sinkholes, the 100-foot radius shall be measured from their discernable edge. At the completion of the investigation the investigator should prepare a Karst Management Plan and the developer directed to follow the specific recommendation embodied therein.

Presence of karst features on the site which will not be impacted – If no karst features are to be affected by the planned development, there will be no need to submit a stand alone karst plan. A statement should be included in the Karst Site Assessment certifying that no features will be impacted.

Description of the Scope Elements

Site Description and Terrain Analysis

The investigator should describe the site, based on examination of the closest topographic mapping available and subsequent field observations. At a minimum, the site topography should be referenced using the USGS 7.5-minute series topographic quadrangle; however it is recommended that 2-foot contour maps or LIDAR (Light Detection and Ranging) be utilized if available (see Figures 2 and 3). In addition, stereoscopic aerial photograph pairs and aerial photo fracture trace analysis may be utilized. Any karst features visible on the topographic map and remote sensing resources (i.e. caves entrances, sinkholes, closed depressions, etc.) should be noted and examined during the field reconnaissance phase of the assessment.

The site description should also include a careful delineation of the property's metes and bounds, and its current use and condition (i.e. vacant land, agricultural land, developed land etc.). Any proposed changes to the site, especially development plans, should be noted and explained in the assessment report.

Description of Soils and Bedrock Geology

The investigator should access the National Resource Conservation Service soil maps for the project site using the web soil survey: <u>http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm</u> Soils data should be examined for the site and adjacent properties, with particular emphasis on the parent materials



Figure 2. Two-foot contour map of a project site, showing a series of closed depressions (sinkhole) in lineaments.

(i.e. whether the soils are residual or transported), their hydrologic characteristics, and textural analysis. Certain soils are noted in NRCS survey data as being "prone to sinkhole formation". These soils should be noted and indicated in the final report. Areas underlain by these soils should be carefully examined even if no closed depressions or sinkholes are noted in the terrain analysis.

Understanding the soils is critical to predicting whether sinkholes will form after a site has been "stripped and grubbed" (i.e. cleared), as highly cohesive soils can often create a "covered" or mantled karst condition where numerous soil-filled or open conduits are hidden beneath the seemingly homogeneous soils cover. Upon removal of the vegetation, the soil will begin to ravel, and previously undetected sinkholes will begin to form.

Bedrock geology should be determined by referencing the highest resolution geological mapping available, ideally at a 7.5-minute topographic quadrangle level. This information can be found by accessing the USGS National Geologic Map Database (ngmb.usgs.gov) or the websites of the local



Figure 3. Topographic Position Index (TPI) showing local topographic concavity and convexity derived from a 1 m LIDAR elevation model and overlain on aerial imagery.

state geological survey. Dip and strike of the bedrock, and any significant structural features (mapped faults, anticlines or synclines, etc.) should be noted.

Field inspection should attempt to verify the mapped soils and bedrock by comparison to the available descriptions. Based on their field observation, the investigator should note whether or not the soils and bedrock conform to the published description(s). If they compare favorably, then no further explanation is required. If they do not, then a detailed description of the differences should be provided.

Description of Surface Drainages and Water Features The investigator should determine the drainage patterns at the site by examination of the topography. The investigator should also check to see if any publicly available hydrological assessments have been performed for the region of interest by state or federal entities.

The analysis of drainage patterns should determine if the site has outlets (i.e. if drainage is directed offsite) or if it is internally drained as these factors can profoundly affect site planning, especially in regards to stormwater management. Drainages to sinkholes should be clearly delineated (Figure 4).



Figure 4. Example drainage map showing sinkhole drainage areas. Note that the drainage area for sinkhole K1 is primarily outside of the site boundary (red line).

The locations of perennial springs, streams and water bodies (lakes, pond, etc.) should be noted. The locations of losing streams (i.e. streams that lose water to the subsurface through their bed), gaining streams, and sinking streams should be carefully noted.

Location and Delineation of Karst Features

Prior to the field observation phase of the assessment, the investigator should access available karst and cave survey databases to determine if any features have been previously located or mapped at the site or on adjacent areas. The National Speleological Society (NSS) has survey committees in most states where there are a significant number of caves, and although the databases of these surveys are technically proprietary, the surveys will share these data with legitimate investigators to assist in conservation and protection efforts. In addition, many karst features have been located by the United States Geological Survey (USGS) and the various State Geological Surveys, and are shown on surficial geology maps, karst survey reports, and other publications. Various state surveys have also published compendiums of cave locations and descriptions in book form, but these publications are seldom complete and need to be supplemented by data that has been collected from the regional NSS surveys. The NSS also has made available through their publication bookstore numerous county level cave surveys which should be accessed if pertinent to the area of interest.

Finally, it is extremely helpful to interview the land owner and/or neighbors regarding the location of any karst features known to them that may exist on or near the survey area. Residents may also know of sinkholes that have been filled or obliterated, cave entrances that have been physically closed, or other features not readily observable during the site inspection. They may also have useful information regarding locations of wet weather springs, seeps, or ephemeral karst lakes and ponds (turloughs) resurgences that are not present during dry weather periods. Alternately, residents may know of locations where water consistently collects and infiltrates into the subsurface. Although anecdotal, it is to the investigator's advantage to examine and verify these observations.

Once the potential locations of karst features have been accessed and noted, the investigator can begin the task of field survey. The site should be examined by a systematic traverse, and each previously identified karst feature should be examined in the field as follows: **Closed Depressions/Sinkholes** – The locations of any closed depression (CD) or area of closed descending contours should be located and examined. The investigator should describe the feature, noting the following parameters:

- 1. What is the general shape of the CD?
- 2. Is the CD actively forming (i.e. are there soil tension cracks around the perimeter of the structure?) or has most of the soil already raveled into the subsurface? (See Figure 5A,5B)
- 3. Is the CD soil-lined or is there exposed bedrock? (Figure 5C,5D)
- 4. Are there mature trees in the structure? What are the estimated ages of the trees? (Figure 5C)
- 5. Does the CD have a "throat" or opening(s) leading into the subsurface? (Figure 5D, 5E)
- Is there any sign that the CD floods or that it is an estavelle¹, such as watermarks, saturated soils, or outflow channel? (see Figure 6A, 6B)
- 7. Is the CD in a topographic position such that it receives drainage from the surrounding area?
- 8. If the answer to question 7 is "yes", does the CD have an obvious drainage channel leading into it, or does it accept only diffuse sheet flow drainage?

The CD should then be measured and delineated. This can be done by the investigator using a hand-held GPS unit, or the structure can be marked ("flagged") in the field and surveyed at a later time. The structure's approximate depth and circumference should be determined as closely as possible and noted, as well as any "nesting" of smaller depressions within the larger ones.

The investigator should be aware of any area where there are signs that water is actively infiltrating into the surface, as this may be an indicator of a subsurface conduit that is soil-filled but receiving drainage (see Figure 7). In this regard, distinct changes in vegetation can be a clue if topographic is slight or absent. These areas should be carefully noted and investigated if they are to be impacted by proposed site development, as they can be the site of sudden and catastrophic subsidence if not managed properly.

Caves – There is a cross-over between caves and closed depressions and sinkholes, as cave entrances are often located within the latter. However, a "cave"

¹A sinkhole which acts as a spring during groundwater highstand conditions, and an insurgence during low stand conditions.

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is traditionally defined as an air-filled opening into the subsurface large enough to allow the passage of a human being. As caves are frequently the home for rare, threatened and endangered species (RTES), often contain important cultural and historic resources, and are environmentally sensitive, it is imperative that they be managed, conserved and protected.

The investigator should attempt to locate and examine any mapped or reported caves on the site. Locations of caves with entrances off-site that may extend beneath the site being studied should also be noted. The majority of significant caves have been mapped, and the investigator should request maps for any onsite or adjacent caves from the regional speleological survey of the NSS. A plan view of the cave showing its route beneath the site is useful to developing a karst management plan. A profile



Figure 5A. Actively forming cover collapse sinkhole in granular sediments.



Figure 5B. Actively forming cover collapse sinkhole in cohesive, fine-grained sediments.



Figure 5C. Mature, stable sinkholes in cohesive soils.



Figure 5D. Mature, rock-walled sinkhole with open "throat" (i.e. cave entrance).



Figure 5E. Soil-bottomed sinkhole with open "throat". A 40' deep vertical cave lies below the opening. This type of structure is sometimes called a "natural trap".



Figure 6A. An estavelle in groundwater low-stand conditions. Note the tell-tale water mark along the rock wall of the structure.

view, showing the cave's depth below the surface, is also important, as caves that are located close to the surface can present a risk to planned development. In contrast, shallow caves can be more readily impacted by releases of contaminants, redirection of surface drainage, and grading activities (e.g. blasting, hoe-ramming, etc.).

As a cautionary note on-site caves should not be entered by the investgator unless they are an experienced spelunker and familiar with the methods and techniques of cave exploration. Caving is an inherently dangerous activity, and should never be done alone and/or without the proper equipment. The local chapters of the NSS,



Figure 7. An area of snowmelt marking a closed depression where water was actively infiltrating into the subsurface. This depression had a relief of less than 2-feet below the surrounding terrain and was not indicated on the site civil engineer's 2-foot contour map. Subsequent Electrical Resistivity Survey (ERS) showed the presence of a soil-filled throat in the bedrock below the structure that was actively channeling surface drainage into the subsurface.



Figure 6B. The same structure as shown in Figure 6A during groundwater high stand conditions. When this photograph was taken the estavelle was an active, ephemeral spring with an outflow measured at 60 gpm.

called "grottoes", generally are glad to help with an assessment by exploring, photographing and mapping a new or unexplored cave.

Karst Drainages and Hydrology – Places where water is either entering the subsurface through a solution feature, or exiting the subsurface through a resurgence (spring) should be located and examined. The locations of perennial springs are generally shown on 7.5-minute series USGS topographic maps. In addition, the landowner or neighbors may have knowledge of springs that have not been mapped or previously marked. Spring flow rates should be measured using accepted hydrological methods and reported.

Insurgences, sinking streams or valley drains (open throat sinkholes that receive surface drainage through a well-defined channel) should be located and described. It should be noted that if a site is internally drained, and a pre-existing insurgence is proposed for use as a discharge point for stormwater, that it falls under the definition of a Class V Injection Well, according to regulations established by the US EPA, and should be registered with the regional EPA office. Many states have their own regulatory requirements for stormwater disposal into sinkholes as well, and these should be checked and referenced if applicable.

The determination of subsurface drainage patterns in karst is a technically demanding and specialized activity, and is typically beyond the scope of a preliminary karst assessment. However, in many well-studied karst regions, major drainages and features have been delineated using dye tracing techniques, and the literature should be searched by the investigator to see if any previous studies have been conducted in or near the area where the assessment is being performed. If ground water monitoring is to be included in the scope of work, then the investigator should employ the techniques embodied in the US EPA guidelines for groundwater monitoring in karst (Quinlan, 1989).

Finally, it should be noted that although they are not natural features, abandoned quarries, drilled wells and hand-dug wells all qualify as openings into the subsurface, and often have direct connection to the phreatic aquifer. As such, these features should also be included in any comprehensive karst assessment.

Covered or Mantled Karst – In many karst settings there is often a relatively thick stratum of cohesive soils lying above the solution-modified bedrock, and these soils can bridge over even air or water-filled conduits. Often there are no obvious karst features to be seen in this type of natural setting, however upon removal of the vegetation and topsoil (i.e. stripping and grubbing) during the preliminary stages of grading a site, cover collapse sinkholes will rapidly form where there seemingly were none before (Figure 8).

Nevertheless, the identification of covered karst is often dependent upon the investigator's knowledge of regional



Figure 8. A pair of cover collapse sinkholes that opened at a site under development after the vegetation and topsoil was stripped. Open throat, air-filled conduits in the bedrock were located at the bottoms of both of these features.

geology, soils, and prior experience with sites in similar geological settings.

Although it can be difficult to locate specifically, if the site is located in an area that the investigator suspects where there may be covered karst conditions present, this should be clearly indicated in the assessment report as covered karst can cause significant delays in construction, and increase the costs of site development well beyond the client's expectations. Therefore, it is strongly recommended that the investigator include a statement in the report's opinions and recommendations section as follows:

As indicated in this report, the bedrock and overlying soil below the site are susceptible to sinkhole development, and karst features are likely hidden beneath the existing soil stratum. Risk associated with sinkhole formation can be minimized during development with proper foundation design and construction, and the control of site hydrology. The Owner/Developer must recognize, however, that a risk of sinkhole-induced damage to foundations, floor slabs, and pavements does exist. The Owner must evaluate the risks and attendant costs of development, and must be willing to accept them.

Location of Shallow Bedrock

The karst terrain is notorious for the presence of shallow bedrock, often with large areas of exposed ledges and shelves. This is particularly problematic due to the fact that much of the carbonate rocks can be resistant to scaling or scarping, and must be either rammed or blasted during the grading process. Areas of shallow or surface exposed bedrock need to be clearly delineated and described in the assessment report.

In areas where the bedrock is steeply inclined, differential solution activity can produce a "pinnacled" bedrock surface, often with exposed bedrock ledges and deep intervening "cutters" in between containing residual soil (Figure 9).

The ledge and cutter terrain is often not considered a sensitive environmental feature by site developers or regional planners, however it can present a significant impact to the subsurface environment if not managed properly. Surface water can migrate rapidly along the interface between the bedrock and the soil filled interstice. During periods of extended drought, the soil



Figure 9. Excavated site cross-section showing pinnacled bedrock with intervening soil-filled "cutters".

fills in the cutters can shrink, and open voids (soil cracks) will form, allowing surface water to plunge into the subsurface, often with direct connection to the phreatic aquifer (Figure 10). Turbulent flow along the interface can also begin the process of soil raveling, sometimes resulting in the sudden formation of sinkholes. In many regions, especially those with cohesive, shrink-swell prone clays, there is often a condition informally referred to as "sinkhole weather" which is characterized by extended dry weather or drought punctuated by periods of heavy rain. Sinkholes will often form when these conditions are present.

Finally, areas of a site designated for storm water management BMPs, especially extended detention and/



Figure 10. The epikarst exposed in an abandoned limestone quarry wall, showing steeply-angled open solutionmodified fractures extending down to the quarry lake. The lake is representative of the local phreatic base-level, and demonstrates how contaminants and surface water can readily migrate to the underlying water table.

or retention ponds or impoundments, must be carefully examined for the presence of pinnacled bedrock.

Exposed pinnacles (Figure 11) can lead both to uncontrolled infiltration of contaminants into the subsurface from the base of the pond, or in the worst case scenario, catastrophic development of sinkholes into which the entire contents of a pond (i.e. water, collected sediment and entrained contaminants) can be disgorged. If pinnacled bedrock is present in these areas the users of the assessment should be made aware of the condition and the risks associated with it.

Exposed pinnacles (Figure 11) can lead both to uncontrolled infiltration of contaminants into the subsurface from the base of the pond, or in the worst case scenario, catastrophic development of sinkholes into which the entire contents of a pond (i.e. water, collected sediment and entrained contaminants) can be disgorged. If pinnacled bedrock is present in these areas the users of the assessment should be made aware of the condition and the risks associated with it.

Follow-Up Studies

If the planned site development will impact karst features at a site, then follow-up studies will inevitably be necessary to thoroughly characterize the impact and help the developer and regional planners understand the risks involved. These studies may include detailed subsurface investigations such as geophysical exploration (e.g. electrical resistivity survey, seismic survey, microgravimetric survey, etc.), borings, track drill exploration, or any combination of the methods. It should be noted that geophysical studies, in particular



Figure 11. Exposed bedrock pinnacles located in the base of a stormwater detention structure in West Virginia.

electrical resistivity survey (ERS), require experienced interpretation which can often be very subjective. In addition, the use of ERS or other geophysical methods without attendant rock probes (coring, track drill, etc.) can often be misinterpreted; however coring or air track investigations carried out without any supporting geophysical evidence of subsurface structures can be wasteful and expensive with little to show for the effort. The two methods should always be used in concert with one another.

The Karst Management Plan

A karst management plan should be prepared for any sites where there is evidence of karst features (i.e. sites upon which karst features are fully or partially located, and/or which drain to offsite sinkholes).

The Karst Management Plan shall include (but not be limited to) the following elements:

- a. A karst feature inventory showing the areal extent of each structure, and a (minimum) 100 foot radius buffer area around the feature;
- b. A topographic map prepared at a maximum 2-foot contour interval, with spot elevations sufficient to determine low points or discernible edges;
- c. A plan prepared by a Geotechnical Engineer to ensure structural stability of principal structures proposed within 100 feet of a sinkhole or other significant karst feature. The plan shall identify tests that will be completed to determine subsurface conditions.
- d. Mitigation recommendations for each karst feature requiring this action. All sinkholes identified prior to construction should be either mitigated or separated from construction. Mitigation should be carried out under the careful observation of the karst professional investigator to confirm site conditions are as predicated in the karst assessment study, and to make necessary modifications to mitigation measures in the event actual site conditions differ from the estimated conditions presented in the study.
- e. The management plan should be reviewed and approved by the county engineering and/ or planning staff prior to approval of site development or issuance of plats.

Closure

It is our hope that this article may serve as a template to assist investigators in conducting comprehensive preliminary karst assessments, and helping jurisdictional regulators, engineers and legislators in determining the minimum elements that should be expected in a site evaluation.

It should be emphasized that the scheme presented herein is not intended to serve as a substitute for detailed subsurface investigations, or to supersede any existing karst regulations or codified protocols.

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GEOTECHNICAL CASE HISTORY FOR SINKHOLE INVESTIGATION AND STABILIZATION METHODS ALONG A HIGH PRESSURE PETROLEUM PIPELINE

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Abstract

Installation of underground pipelines through unpopulated land situated over pinnacled carbonate bedrock can lead to the development of sinkholes. The formation of sinkholes beneath buried pipelines has the potential of damaging the pipeline and more importantly causing hazardous environmental incidents.

This paper presents a case history at a site where significant sinkholes developed within and adjacent to a 400 foot (112 meters) long section of high pressure petroleum pipeline right-of-way that crosses under a local creek in Plymouth Meeting, Pennsylvania.

Various geophysical investigation techniques consisting of microgravity, multi-channel analysis of surface waves (MASW), and two dimensional electrical resistivity testing were performed in addition to confirmatory testing borings to effectively evaluate the subsurface conditions at the site. Three options were considered as a solution to the active sinkholes present within the pipeline rightof-way. These options include: 1) subsurface grouting within the right-of-way 2) structurally supporting the pipeline on a deep foundation system or 3) relocating the pipeline to a less sinkhole prone portion of an adjacent property. Following the investigation process, relocating the pipeline in conjunction with pre-installation ground improvements via subsurface grouting represented the most cost-effective, lowest risk solution at the site.

Introduction

In January 2009 a sinkhole developed below an active petroleum pipeline that crossed under a local creek in Plymouth Meeting, Pennsylvania. Upon initial discovery, it was reported that the sinkhole measured approximately 9 feet (3 meters) in diameter by 9 feet (3 meters) in depth causing the pipeline to be unsupported across a portion of the open void. Representatives of the pipeline company filled in the sinkhole with various materials that ranged from tree stumps to geotextile filter fabric and well-graded aggregates as a temporary solution to the problem. Following the temporary backfill measures, the owner recognized the severity of the problem and the need for the expertise of a geotechnical engineering firm.

Initially, a feasibility study was conducted to determine the most cost-effective and best long term solution at the site. The options considered include: 1) subsurface grouting within the right-of-way 2) structurally supporting the pipeline on a deep foundation system or 3) relocating the pipeline to a less sinkhole prone portion of an adjacent property.

The first step in the study was to perform a site reconnaissance and a stereographic aerial photograph review. Due to the site being primarily wooded, inconclusive results were found from the aerial photograph review. During the site reconnaissance, the streambed was dry on each side of the pipeline crossing. The stream bed remained dry for approximately 500 to 600 yards (457 to 549 meters) upstream of the sinkhole at the pipeline crossing. Further inspection revealed a large sinkhole had created a disappearing stream condition upstream of the pipeline crossing. Photograph 1 shows the large sinkhole upstream of the pipeline crossing.

The overall topography within the pipeline right-of-way slopes gently to moderately downwards toward the creek and sinkhole locations. Photograph 2 shows the area of study within the pipeline right-of-way.

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Project Description and Background

During low flow conditions, the creek water disappears into the upstream sinkhole leaving the downstream side dry. During periods of steady rainfall, storm water



Photograph 1. Sinkhole within creek bed.



Photograph 2. Pipeline right-of way crossing local creek.

fills the large sinkhole upstream and continues to flow down past the pipeline crossing. Numerous additional sinkholes are present on the western bank of the stream between the disappearing stream location and the sinkhole at the pipeline crossing. At the conclusion of the first phase of the investigation, it was evident that the immediate region is highly active and warranted further means of investigation.

Two separate geophysical investigation methods were initially performed within the referenced section of pipeline right-of-way and portions of the streambed on each side of the right-of-way. The first method, microgravity, provides a broad interpretation of the subsurface conditions and the second method, multichannel analysis of surface waves (MASW), provides a linear profile of the subsurface below the pipeline. The combination of the geophysical methods provides a relatively accurate depiction of the subsurface conditions within the area of study.

The microgravity investigation provides spatial coverage of the investigation area. "Broad areas of higher gravity indicate relatively shallow rock (potential pinnacles) and broad areas of lower gravity indicate relatively deeper rock (voids). In microgravity surveying, fractures and faults are typically observed as linear low gravity anomalies because the fractured rock tends to be less dense than the bounding non-fractured rock" (Lee, 2012, email communication).

The study conducted at the site consisted of recording microgravity readings in a 10 foot (3 meters) by 10 foot (3 meters) grid pattern. Features such as voids in the bedrock and/or weak soil conditions appeared in sharp contrast to dense soil or bedrock. In addition, potential faults and fracture traces were also generated from the microgravity investigation. The results of the microgravity readings at each grid station are plotted in color and a microgravity contour map is generated to provide a clear interpretation of the subsurface conditions to the viewer. Figure 1 shows the results of the microgravity investigation.

The results of the microgravity investigation clearly depict that subsurface conditions in the vicinity of the 2009 sinkhole location are highly variable with dense, shallow rock on the eastern and southern side of the creek and less dense, deeper overburden soils on the north and west side of the creek. Interpretation of the survey also revealed the presence of a potential fault that trends in a general northwest-southeast lineation. The fault extends between the pipeline and the northern edge of the pipeline right-of-way where the deeper overburden exists. Consequently, a majority of the sinkhole activity is on the north side of the fault. Two parallel fractures also exist in line with the creek and perpendicular to the fault line. It is significant to note that sinkholes have an increased risk of development in proximity to the intersection of fractures and faults in the underlying bedrock. Accordingly, at this site, sinkhole locations coincide with the location of intersecting fractures and faults. Further exacerbating sinkhole activity is that the topography generally slopes downwards in all directions



Figure 1. Microgravity results.

toward sinkhole areas. The sinkholes are also at an apparent transition location between the shallow dense rock on the south and east side of the pipeline and deeper and less dense rock on the north and west side. Competent bedrock tends to be a barrier to stormwater infiltration such that during a period of surficial stormwater flow over the sinkhole area, the infiltrating stormwater deflects off the shallow, pinnacled rock surface and carries away loose soil and rock material to accelerate the sinkhole activity (Lee, 2010).

Following the microgravity investigation, the secondary geophysical method consisting of MASW was performed adjacent to the existing pipeline. The MASW method was used to provide a linear geophysical profile of subsurface conditions directly below the pipeline. The MASW could not be completed within the stream channel where rip rap was present. The MASW profile was generated from the interpretation of shear wave velocities generated by striking a plate attached to the ground. Geophones, spaced along selected intervals of the array record shear wave velocities as function of distance from strike point. From this data, material properties and depth to bedrock were estimated (Lee, 2010). The results are presented in Figure 2. After the completion of the geophysical investigations, 13 test borings were performed in proximity to open sinkholes, over anomalous subsurface conditions identified in the geophysical surveys, and where dense shallow bedrock was interpreted to exist. The intent of the test borings was to verify the conditions found in the geophysical investigations. Standard Penetration Tests (SPT) were performed at regular intervals throughout the borings until auger refusal was achieved. Following refusal



Figure 2. MASW results on western side of creek.

on the bedrock surface, rock coring was performed to evaluate the condition of the underlying bedrock.

As expected from the geophysical testing, the results of the test borings revealed highly variable conditions. The depth to bedrock ranges from seven feet beneath the existing ground surface to in excess of 70 feet (21 meters). The large variation in depth to bedrock exists in two test borings drilled approximately five feet (1.5 meters) apart. Interpretation of a boring drilled near the 2009 sinkhole location and near the pipeline revealed an 11 foot (3.3 meters) continuous void in the bedrock, starting at three feet below the soil/bedrock interface. This void was encountered during the rock coring operation. In areas where subsurface anomalies were found in the geophysical investigation, the test borings confirmed voids in the subsurface. Figure 3 displays the relationship between the results of the microgravity investigation to the conditions found in the borings. The test boring results are displayed on a subsurface profile situated above a plan view of the microgravity results in Figure 3. This figure shows the strong correlation between the two methods and confirms the advantage of using microgravity to determine subsurface conditions.

As a result of the conditions found in proximity to the pipeline by the geophysical investigations and confirmed by the test borings, an emergency "stopgap" grouting operation was performed utilizing a permeation grout. This stopgap grouting program was developed in an attempt to minimize the potential of failure below the pipe while a long-term solution could be determined. A permeation grouting method was chosen based on criteria of attempting to fill voids/fractures in the bedrock as well as minimizing the potential for heaving the active pipeline. The permeation grout consists of a high slump neat cement that can easily flow into fissures and fractures at the soil/bedrock interface. Due to the clayey nature of the overburden soils, grouting was only intended to fill voids in the bedrock. During the grouting, no backpressure was recorded indicating a significant sized void was accepting the grout. A total of 40 cubic yards (12.1 cubic meters) of grout was injected into the subsurface without recorded backpressure.

The results of the geotechnical investigation revealed that active sinkhole conditions were present in the existing pipeline right-of-way. As part of the scope of work, a budgetary value of \$600,000 was estimated for a remedial grouting operation within the pipeline rightof-way. Due to the extensive voids found in the borings, the large amount of grout required during the stopgap grouting operations, and the potential for extensive active sinkhole conditions near the pipeline, concerns were raised that the grouting costs could easily exceed the budget estimate. Therefore, a subsurface grouting program within the existing right of way was considered to be cost-prohibitive. Furthermore, due to the variable subsurface conditions and depth to competent bedrock found within the right-of-way, a deep foundation system to structurally support the pipeline was not considered viable due to the high costs associated with this option.



Figure 3. Test boring profiles results and a plan view of the corresponding microgravity results along the creek perpendicular to pipeline.

At that juncture, options to investigate relocating the 400 foot (122 meters) long section of pipeline to a less sinkhole prone location were evaluated. A triangular shaped, undeveloped tract of land is situated directly south of the 400 foot (122 meters) long section of existing pipeline. Once permission was granted to investigate the land to the south, a second phase of work at the site commenced.

Since the purpose of the second phase was to evaluate an optimum route to relocate the pipeline, a proactive approach was taken. The new process consisted of performing an initial microgravity survey in a grid pattern to spatially identify subsurface conditions. After evaluation of the microgravity results, a proposed pipeline alignment was selected in areas identified with shallow rock and minimal anomalies. Figure 4 displays the results of the microgravity results within the available land to the south of the existing right-of-way and the proposed pipeline relocation route.

After the preferred relocation alignment was chosen, MASW and two-dimensional electrical resistivity (2D ERI) surveys were conducted to provide a linear profile of the subsurface conditions beneath the new alignment. The 2D ERI was used in areas of steep slopes or undulating ground surface. Following the geophysical surveys, test borings were drilled at anomaly locations



Figure 4. Microgravity results included with MASW & 2D ERI locations over the proposed realignment route.



Figure 5. Test boring locations conducted in realignment route.

identified in the new geophysical testing. Figure 5 displays the test boring locations chosen based on the geophysical testing. Analysis of microgravity data from the new alignment revealed that relatively shallow and dense rock was present with isolated anomalies in most of the new alignment. However, analysis of the 2D ERI and MASW data in the relocated alignment revealed low density bedrock in the initial 70 feet (21.3 meters) of the proposed new pipeline in the vicinity of boring B-111 shown in Figure 5. Additionally, isolated anomalies are located along the remainder of the proposed relocation route. As before, strong correlation was found between the geophysical data and the new boring data.

Within the initial 70 feet (21.3 meters), a medium dense fine grained clayey soil was encountered above the rock surface. However, soil seams, voids and generally poor quality rock were found in the bedrock. Along the remainder of relocation route, some isolated areas of weak soil, voids in the bedrock and poor quality rock exist. Further complicating the new alignment is that poor quality carbonate rock is more susceptible to dissolution and weathering than higher quality rock.

Analysis of the data recorded during the field investigation for the new alignment indicated that a ground modification program is required. The recommended program consists of a subsurface grouting program along portions of the proposed relocation route prior to installation of the new pipeline. The grouting program is required within the initial 70 feet (21.3 meters) of the new pipeline location as well as in areas where the isolated anomalies exist. A grout curtain is to be installed along a portion of the right-ofway where a fracture trace exists. Since sinkholes have a tendency to develop over fractures in the bedrock, the grout curtain is expected to reduce the potential of sinkhole development by cutting off potential flow path(s) in the underlying bedrock.

The recommended subsurface grouting program is based on the level of risk for potential sinkhole formation identified through the geophysical investigations and test boring operation performed. In areas that possess the greatest risk for sinkhole activity, targeted grouting is recommended to be performed in a grid pattern around the identified features. In order to further reduce the risk for sinkhole activity, additional compaction grouting is recommended in between the targeted locations, every 10 feet (3 meters) on center below the centerline of the proposed pipeline. Figure 6 displays the proposed grouting location plan.

The grouting program is recommended to be performed in phases. As shown in Figure 6, the black circles display the phase 1 grouting locations and the red triangles display the phase 2 grouting locations. The phase 1 grouting locations consist of installing casing into the bedrock where voids, soil seams, or poor quality bedrock is located. Grouting during the phase 1 operation extends from the voided areas within the bedrock to a depth of 2 feet (0.6 meters) below the proposed bottom of trench elevation. During the phase 2 grouting, the casing terminates at the soil/ bedrock interface and extends upward to the same depth criteria referenced for phase 1. Within the initial zones for each application, a higher slump material is used to allow the grout to permeate into the voids/ fissures and fractures within the bedrock. As the grout casing is raised into the overburden soils, the slump is adjusted to create a low mobility grout similar to compaction grout. The pumping rate is maintained at 1-2 cubic feet per minute (0.3 to 0.6 cubic meters per minute) since a high injection rate can cause hydraulic fracturing (Warner, 2004). The grout volume injected per 2 foot (0.6 meters) stage is recommended based on the backpressure recorded at the given depths. Table 1 provides the recommended pressure versus grout volumes per 2 foot (0.6 meters) stage.

A typical subsurface density profile over carbonate bedrock suggests that the upper crust close to the ground

TABLE 1. Grout volume cut-off criteria.		
Recorded	Volume of Grout	
Backpressure	to be Injected	
0-50 psi	1.0 yd3/stage	
(0 - 344.7 KPa)	(0.764 m3/stage)	
50-300 psi	0.5 yard ³ /stage	
(345–2068 KPa)	(0.382 m ³ /stage)	
300-400 psi	0.25 yard ³ /stage	
(2068 – 2758 KPa)	(0.191 m ³ /stage)	
> 400 psi	Pressure cut-off –	
(2758 KPa)	raise to next stage	


Figure 6. Proposed grouting location plan within realignment route.

surface is typically characterized by stiffer clayey soils. As the depth increases, a decrease in stiffness or density and a gradational change from fine grained to more coarse soils is typically found above the fractured carbonate bedrock surface. When steel casing from the grouting program is installed to the bedrock surface, the grout is expected to flow easier into the typical fissures and fractures at the soil/bedrock surface. The intent is to seal the open "throat" in the rock surface. As the steel casing is raised into the lower zones of the overburden soils, a low mobility displacement grout is used to densify surrounding weak zones of soils and fill any remaining voids that exist near the soil/bedrock interface. Within the zones of the weak soils, it should be expected that the higher volumes of grout will be experienced. As the casing is raised into a denser soil

matrix and grouting continues, a decreased volume of grout injection is expected due to the denser soils and higher backpressures. Figure 7 displays the expected results of the recommended grouting operation.

Conclusions

This paper shows that geophysical testing using microgravity, MASW, and 2D ERI can predict the occurrence of active sinkholes in pinnacled carbonate bedrock. If subsurface grouting is being considered as a method for sinkhole stabilization or treating sinkhole prone site, a comprehensive geophysical and geotechnical investigation will significantly aid in developing an effective scope of work for the project by identifying specific areas and depths requiring ground improvements. The information gathered is also



Figure 7. Conceptual sketch of grouting. Base sketch used to show grout from J.P. Wilshusen & W.E. Kochanov, The Geology of Pennsylvania, 1999.

instrumental in developing a cost estimate for the ground improvement work. Furthermore, by basing the volume injected on the grout backpressure recorded at each stage, a more efficient grouting operation can be expected which may limit the potential for future sinkhole re-occurrence. By engaging a geotechnical engineering firm in the early stages of project development it is possible to provide options to reduce the risks of sinkhole development and reduce costs for potentially problematic sinkhole recurrence.

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PROBLEMS ASSOCIATED WITH THE USE OF COMPACTION GROUT FOR SINKHOLE REMEDIATION IN WEST-CENTRAL FLORIDA

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Abstract

Compaction grouting is a widely used method for sinkhole remediation. It is generally less costly than other methods of remediation and provides a less intrusive method of repairing adverse subsurface conditions. However, we believe that many engineers in preparing specifications and contractors in construction practice have improperly applied compaction grouting as a method of remediation. In some cases, improper use of compaction grout has resulted in the deterioration of marginal subsurface conditions significantly increasing the cost of repair and inconvenience to the homeowner. Another consideration in the selection of compaction grout is the occurrence of subsurface conditions in which deep foundation support should be used rather than the seemingly less expensive compaction grout method. This manuscript discusses techniques in the proper use of compaction grouting and the precautions that should be taken before, during and after compaction grouting. It also discusses potential conditions when compaction grouting should be supplemented or replaced with deep foundations. Included in the manuscript are compaction grouting case studies and recommendations for the proper application of compaction grout.

Introduction

Compaction grouting is a common method used to remediate homes affected by sinkhole activity. It generally provides a relatively fast, effective and economical method of soil improvement. The compaction grouting process consists of injecting, under high pressure, a stiff mortar-like grout into the ground to displace, fill voids and compact the surrounding soil. The common practice is to apply compaction grout from the rock surface upward (upstage grouting) by building successive segments of grout such that one segment rests on the segment below until the grout reaches the desired depth. Fundamental to the success of the grouting procedure is deposition of the grout in a globular mass (typically either columnar or tear-shaped) at each injection location (Warner, 2004). In theory, the volume of grout placed in the ground will cause an increase in density in loose sandy soils as the expanding grout displaces soil and thus compacts and increases the strength of soil between the successive grout columns. Although some benefit will be obtained from the compressive strength of the grout columns placed typically six to ten feet apart but terminated 10 to 15 feet (3.0 to 4.6 meters) below the ground surface; however, the primary use of this method is for soil densification through compaction. Another function of the grout is to seal any seepage paths that may exist at the rock soil interface.

Grout Application Problems

Detracting from the benefits of compaction grout are problems that occur when grout is placed at a high flow rate causing hydraulic fracturing of the soil. In this instance, high pore pressures develop that cause the soil to fail in an undrained state, remolding the soil into a liquefied mass that moves in response to the high pore pressures generated by the rapidly expanding grout front (see Figure1).

The hydraulic fracturing interferes with the orderly compaction process and can cause damage in the building under which grout is injected and in nearby buildings. Damage to overlying structures can be caused by the increase in overburden weight from the soil that has been intruded by lenses of grout as shown in Figure 1. The increase in soil weight can sometimes result in settlement of the building being remediated. Nearby buildings can also be damaged from the intrusion of grout into utilities and into the building.

Some assert that contactors monitor heave while pumping and pumping can be stopped when movement is seen. This sounds reasonable in theory but in practice there are a number of problems. First, there is a time lag from the time the inspector happens to notice movement till the time he communicates that to the pump operator.

Grout Flow < 2 - 5 cf/min

Grout Flow > 5 cf/min



Figure 1. Adverse effects of high flow rates.

Second, once movement starts it may continue for a period because of pressure in the formation. Third, when movement occurs, even if it stops when pumping is stopped, it may be too late, the building can be immediately damaged.

These problems, in many cases, pale relative to the greatest impetus to increase grout flow rates, to the highest possible rate. This is the increased cost for pumping grout at low flow rates. The lower flow rate increases the time required to complete the grouting hence labor and equipment costs increase for the grouting contractor and for inspection. Costs for supply of grout also increase because of the increased time to use the grout. Typically, most contracts adhere to ASTM C94 requirements for discharge of the concrete within a $1\frac{1}{2}$ hour period from batch to placement. If this time is exceeded the concrete cannot be used. This means that instead of the grout supplier providing 10 cubic yard trucks they must deliver grout in 5 cubic yard trucks. This obviously decreases the supplier's efficiency and therefore increases cost.

A significant part of the grouting procedure is that no one actually sees the completed product—it is unseen below the ground surface. Only when something goes wrong such as damage to the home, grout deposited in a neighboring property or settlement sometime after completion of remediation is the grouting procedure questioned. By that time it is too late to correct the problem; all that can be done is deal with the difficulty and conclude that this is one of the shortfalls of compaction grouting. The delay in determining if the grouting was successful is a concern for all and is minimized by the procedures discussed.

Recommended Methods of Resolving Grout Flow Problems

A solution to the dichotomy of cost verses compaction grout quality that considers both technical and economic factors is to determine the critical flow rate at which hydraulic fracturing occurs in soft soil areas. This is done by increasing the flow rate until a decrease in grouting pressure occurs (presumed to be the onset of hydraulic fracturing of the soil). The procedure is performed in known areas of soft soil found in existing borings or at the location of soft soil conditions found in the newly installed grout holes. The production flow rate is determined based on a value of 90% of the flow rate that causes a decrease in pressure or in any area where an increasing flow rate results in a decrease in pressure. In other areas, with different soil properties, a flow rate of 5 to 7 cubic feet per minute (0.142 to 0.198 cubic meters per minute) is used.

Variable Soil and Rock Conditions

It is important to use all subsurface information that is available to analyze the diverse conditions that occur in karst terrains. To determine potential areas where soft soil conditions may be present for use of the low flow rate, it is recommended that consideration be given to the depths to sound rock found in the grout drill holes. Figures 2 through 5 show two sites where grout hole information is known. The point in illustrating this data is to show the stark difference in the interpretation that occurs when additional information is available. Compare the differences in the depth to rock found from grout holes where rock information is on 10-foot (3.0 meter) centers as opposed to information obtained from SPT borings where distances between data points are very great. The grouting data points show the extreme variability in the rock surface that was not found in the SPT data. Therefore, the advantage in using grout hole data is that one can anticipate where soft soil conditions may occur-in karst areas this is common in locations of abrupt changes in depth to rock. The lower grout flow rates should be used in areas of abrupt changes in depth to limestone.

When Not to Use Compaction Grout

If more than several inches of settlement have occurred in a structure, lifting a building component should be accomplished through means other than compaction grouting such as by use of pin-piles (small diameter piles commonly referred to as mini-piles, micro-piles and pinpiles having a diameter from approximately 0.3 to 1 feet [0.1 to 0.3 meters]). Small adjustments for settlement can be accomplished by the use of chemical grout (polyurethane foam in low viscosity liquid form pumped at low pressure into cohesionless soils) where loads and the amount of lift are small. However, larger lifts may be accomplished with chemical grout on some slabs with moderate loads depending on geometry and loading.

As a side note, an often-overlooked property in the use of pin-piles is the quality of the rock material used to support the piles. The limestone rock surface tends to be highly solutioned and weathered resulting in a surface of questionable integrity to support a load. Unfortunately, the quality of the limestone rock used to support the pin-piles is often not properly investigated to determine its competency. Figure 6 provides an illustration of a typical limestone surface that may be encountered for support of pile loads. When these conditions are anticipated, an additional subsurface investigation should be performed to determine the integrity of the rock.



Figure 2. Depth (in meters) to sound rock from borings in Site 1 (no horizontal scale).



Figure 3. Depth (in meters) to sound rock from grout holes in Site 1 (no horizontal scale).



Figure 4. Depth (in meters) to sound rock from borings in site 2 (no horizontal scale).



Figure 5. Depth (in meters) to sound rock from grout holes in Site 2 (no horizontal scale).



Figure 6. Typical limestone surface.

When large thicknesses of very soft (weight of hammer/ weight of rod, WH/WR) soil conditions are found in the order of greater than 20 feet (6.1 meters), a cost comparison should be performed to determine which method is economical. The analysis should include the cost for pumping grout at reduced flow rates and the cost for additional investigation of the quality of the rock surface to support a pile load.

Other Considerations

The use of compaction grouting is directed to remediating soft soil conditions; however, in doing so, areas of dense soil will inadvertently be subjected to compaction grout. The net result is that the grouting process may loosen these areas. When large areas of dense soil are known to be present on a site, the extent of the grouting program should be re-evaluated after grout hole data is available to determine the grouting effort to be used in the various grout holes.

Conclusions

It has been discussed that:

- 1. The use of high grout flow rates results in unacceptable lateral displacement of the grout extending in lens-like fashion to substantial distances beyond the point of placement. This causes remolding of the soil greatly adding to the weight of the composite grout-intruded soil (Figure 1).
- 2. A production flow rate should be determined based on a value of 90% of the flow rate that causes a decrease in pressure in soft soil areas or in any area where a decrease in pressure is found. In other areas a flow rate of 5 to 7 cubic feet per minute (0.142 to 0.198 cubic meters per minute) is used.

- 3. The net increase in soil weight, due to a high flow rate injection, can cause settlement of the underlying soil and the building foundation supported by the soil (Warner).
- 4. Compaction grout is not a process where the weight of the building is supported on a column of grout; it is a process where compaction of the soil occurs from the inclusion of a volume of grout between successive grout columns compacting the soil and increasing soil strength. The strength of compaction grout is only required to meet or exceed the in situ soil.

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EVALUATING KARST RISK AT PROPOSED WINDPOWER PROJECTS

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Abstract

Karst can cause a litany of problems for a windpower project, and it is good practice to evaluate karst risk before proceeding with a proposed project. Windpower projects involve widely-spaced structures with small footprints that can cost \$2 million to \$5 million each. Financial viability can prove difficult, so it is important to find useful, inexpensive procedures for evaluating karst risk. The karst-risk-review process we have used can be split into the two categories outlined below.

Desktop studies:

- Search for relevant literature
- Review aerial-photo and map, and analyze lineament
- Search for existing well and boring logs
- Survey local experts—landowners, U.S. Geological Survey, state geological survey, cavers, etc.

Field studies:

- Perform site reconnaissance
- Conduct pit tests if bedrock is shallow
- Drill—A normal geotechnical investigation includes one boring per turbine, while karst investigations may include multiple borings per turbine
- Use a downhole camera—May be useful in evaluating extent of voids and convincing clients of risk.
- Conduct geophysical studies

Effectively communicating with developers is critical. They want to know the location of the problem sites and may ask, If there is a cave, what is the chance that a turbine will fail? The geo-professional needs to do the following effectively:

- Explain the short-term (collapse) and long-term (settlement) risks, and mitigation options
- Explain the uncertainty
- Negotiate liability
- Costs of investigation and mitigation
- Get developers to determine how much to spend while understanding how much incremental-risk reduction they will receive

The discussion of karst risk should be ongoing and investigations may proceed on a step-by-step basis as new information is gathered. It's important to determine whether to investigate all sites underlain by a potentially karstic unit or try to rank the sites based on risk before focusing the investigation on those with potentially higher risk. Perturbine karst investigation costs can easily reach \$20,000 and more, so investigating each site in a 100-turbine development can be a significant commitment. When possible, start karst evaluation early, manage available cash with a stepwise approach, and communicate.

Introduction

There are no clear-cut approaches for measuring or mitigating karst risk. Unlike flooding risk and seismicity risk, karst risk is not addressed by the Federal Emergency Management Agency or the USGS. Karst may or may not be addressed by local building codes. Karst-risk assessment is further complicated by the remote, sparsely-populated, and undeveloped areas that are often chosen for wind farm sites. In these areas, there is a limited frame of reference for observing subsidence, fewer eyes observing the ground, and, normally, no reason for anyone to care about sinkholes. A sinkhole in downtown Miami gets more attention than a sinkhole in rural Texas.

Karst can lead to a wind turbine tilting and even toppling. Also, subtle differential settlement of even 3 centimeters across a 15-meter-wide wind turbine foundation can cause the turbine to be out of tolerance and lead to expensive and time-consuming remedial action. Turbines need to be widely spaced for optimum performance (see Figure 1), so each proposed turbine location may need to be evaluated independently for karst risk. An installed turbine can cost \$2 million to \$5 million, so the liability is high.



Figure 1. Typical wind farm. Note widely-spaced wind turbines in a remote setting.

Figure 2 is a section of a turbine illustrating the major forces: the wind load, dead load, lateral load, and overturning moment. Turbines have relatively low dead loads but relatively high overturning moments. While there are several types of foundations that can be used, the most common by far is the spread footing shown on Figure 2. The discussion in this paper generally assumes and relates to the use of spread footings. Note that the overturning moment is such a significant factor that ground strength rarely affects the foundation diameter.

Commercial scale windpower projects typically include 10-100 turbines. Employing a common foundation design across the project aids in the economic viability. When a project requires customization of a foundation or foundations to address site-specific conditions, the economics of a project can become untenable.

Figure 3 shows the basic timeline for building a typical wind farm. Once a promising site is identified, several years are spent completing the development phase. When a project enters the development phase, it is still relatively speculative and available funds are limited. As a project moves along the development process—

stepping forward toward viability—more funding becomes available. The additional funding affects the karst-evaluation process. Karst evaluation should be stepwise so the early karst evaluation phases can be completed inexpensively, and the more expensive phases are done later when more funding is available.

If possible, the karst professional needs to educate the developer and work with him/her to use funds efficiently. Note that many developers structure projects so that the geotechnical investigation and foundation design are packaged with the construction. In these cases, the issues and implications of karst may come as a surprise, at a point when there is no turning back—the turbines have typically already been purchased. Once in construction, a client has little patience – "just tell me what to do", is the common reaction, until faced with what karst evaluation can cost.



Figure 2. Typical turbine section and major forces. Spread footings are most common. Hub heights 80-100 m (but can go up to 120 m); foundation width 15-22 m; foundation embedment 2-3 m; overturning moment: 35,000 kN*m - 110,000 kN*m; dead load: 1,850 kN - 5,100 kN



Figure 3. Timeline for developing and operating a typical wind farm.

This paper will address:

- the typical karst investigation methods
- the ways karst risk can be mitigated
- the issues that must be addressed in communicating with the client
- some brief project examples

Investigation Methods

Keeping a windpower project financially viable can prove difficult, so there is pressure to find useful ways to evaluate karst risk while keeping costs under control.

We have followed a commonly used program (Fischer et al. 1987 Roux, 1987; Tonkin & Taylor LTD, 2011).

Not every tool is necessary or appropriate for every site:

Desktop studies:

- Literature search
- Aerial-photo and map review, lineament analysis
- · Existing well and boring logs search
- Survey of local experts

Field studies:

- Site reconnaissance
- Pit tests
- Geophysics
- Drilling (may include downhole camera and downhole mapping methods)

These methods are listed, approximately, in the order of increasing cost. Because of their cost, drilling and geophysics are usually not undertaken until late in the development process or once the project goes to construction. Hence, available geologic information, especially from geological surveys, is often extremely useful and low-cost.

Literature searches are commonly used on all manner of geologic studies, and there is no need to discuss them further here. One example of something that may be identified at this stage is a stratigraphic correlation to karst occurrence. For example, much of southeastern Minnesota is underlain by carbonate bedrock, but in Mower County the karstification is most developed in the Lithograph City Formation (Green et al., 2002). Well logs are a valuable source of information. More and more, states are making water-well information available online. Some examples include:

- Iowa http://www.igsb.uiowa.edu/about/geosam.htm
- Minnesota http://www.health.state.mn.us/divs/eh/cwi/

Using remote-sensing techniques is another investigation method with a long history. Maps often show the locations of karstic features, especially springs and sinkholes (Figure 4). USDA Natural Resources Conservation Service soil mapping also includes sinkholes and other karst features for many areas and is available nearly nationwide in GIS format at http://websoilsurvey.nrcs. usda.gov/app/HomePage.htm. Trained and experienced staff can review aerial photographs and topographic maps for apparent karstic features. Today, much of this information is available online, but it is still important to look for historic aerial photographs so the site can be viewed from different perspectives relative to the season and time of day. Modern methods such as interferometric synthetic aperture radar and digital elevation models may be particularly valuable.

Karst features tend to form along pre-existing fractures, and epikarst development associated with the deeper karst is commonly why lineaments are expressed on the ground surface (Lattham and Parizek, 1964; WVGES, 1979). While it is hardly definitive, a lineament analysis should be conducted, where appropriate, to identify potential high-risk areas (Figure 5). Some geologic terrains have relatively thick soil covers unrelated to the bedrock that can obscure bedrock lineaments. Lineament analyses have limited or no application in these areas.

There is more than one type of karst, and investigations and mitigation must be appropriate to the local conditions. Local experts are a significant source of information. A good example is co-author Ken Johnson, whose experience in Oklahoma with evaporite karst was invaluable in evaluating evaporite karst risk at the Watonga project in Oklahoma (Johnson et al., 2013). In addition to geological surveys, other geologic experts can be identified during literature searches or found in local colleges or consulting firms. Non-technical sources can include landowners and speleological societies. These non-technical sources can be unreliable and/or



Figure 4. Map of proposed wind farm development area showing mapped karst features and one example of lineation of features.



Figure 5. Map of a Scurry County, Texas Wind farm project area showing mapped lineaments. Labeled dots are proposed turbine locations.

uncooperative because landowners may be concerned about the effect of karst on their land value, and cavers are often reluctant to share private mapping with outsiders or may be philosophically opposed to the project.

Site reconnaissance is important for the general characterization of the area. It may also identify karst features near or at individual turbine sites. Classic geological field techniques and experience with karst are important because so much cost and risk can be based on early findings and decisions. If possible, access to quarries is especially valuable even if outside the immediate project area.

Where bedrock is shallow, test pits can be useful in evaluating the bedrock surface and investigating the nature of depressions to determine whether or not they are related to karst formation.

A normal geotechnical investigation includes one 15- to 25-meter deep boring per turbine. This depth is about equal to the width of the turbine foundation, and the depth is chosen based on the vertical stress induced by the foundation (Das, 2010). Karst investigations may include multiple borings per turbine. The question is, how many are required to assess karst risk? Advanced geotechnical modeling can provide an indication of the size of void verses depth that may be problematic. However, modeling is expensive, especially if conditions vary across the proposed wind farm, requiring multiple models. The cost of drilling multiple borings per turbine.

A downhole camera can be used in conjunction with drilling. This can be especially useful in convincing the client that there is a risk. Although not used by these authors, laser scanning and 3D mapping may also prove useful.

The use of geophysics in karst evaluations is well studied and reported, and it is regularly addressed at karst conferences (Beck and Wilson, 1987; Beck and Stephenson, 1997; Beck, 2003), including this one. No single technique works everywhere. Ground penetrating radar is one of the most widely-available geophysical tools, but it rarely attains a useful depth of penetration; the base of a turbine foundation is typically 2 to 3 m below grade. In fact, most geophysical methods lack the fine resolution required to characterize risk. A relatively small void occurring 4 m below grade could be difficult

to image, yet it would pose significant risk to a turbine. In many karst areas, soil piping presents a major risk for the creation of a void that doesn't currently exist. At its best, geophysics identifies anomalies. The nature of the anomalies must then be determined through drilling.

Risk characterization has a number of questions:

- Is the subgrade potentially subject to karst formation?
- Are there any known karst features in the region?
- Are there karst features in the project area?
- Are there karst features at the proposed turbine sites?

The results at each stage of evaluation are used to determine if more investigation is required and, if so, the scope of the next phase.

One of the most difficult situations is where there is shallow carbonate or evaporite bedrock and no evidence of karst from the desktop phase or reconnaissance. The lack of evidence does not mean there is no risk. The question then is, how much investigation is required? Lineament analysis has been used to identify areas with higher potential risk. Then, intense investigation can be completed in these areas. If no subsurface voids are found, it may be acceptable to forego further karst investigation in other areas.

Risk mitigation

Once karst risk has been confirmed and characterized, mitigation must be applied. More than one method of mitigation may be used on a windpower project. There are several ways of mitigating karst risk:

- Move the turbines at risk. It may be possible to determine low-risk and high-risk areas. The high-risk sites can be abandoned. Developers have learned to include alternative locations early in the process for this type of outcome. Depending on the number of sites that are eliminated and the number of alternate sites, the cost may range from practically nothing to the loss of the investment and revenue related to the net lost sites.
- **Conduct detailed investigation.** Some developments may have very limited constraints on where turbines can be placed, and distant low-risk alternative locations may not be available. A developer can then decide to do more intensive

investigation of a proposed turbine location to see if moving the turbine a short distance can reduce risk. This method of mitigation can add tens of thousands of dollars and may not be successful.

- Provide thick soil cover to mitigate the risk of subsidence. In some areas, thick soil unrelated to the bedrock (glacial till, wind-blown deposits) may provide an effective bridge over bedrock karst features, and soil thickness may be preliminarily determined based on existing mapping and drilling logs. Eventually, each proposed turbine site should be drilled to determine actual soil thickness. However, the question of how much soil is enough needs to be answered. There may be precedents. Goa et al. (2002) found that most surface karst expressions in Minnesota occur where there is less than 15 m of glacial cover. The Minnesota Geological Survey's Mower County geological atlas (Green et al., 2002) concluded that evidence of karst features was not found for areas with more than 23 m of glacial cover. For the proposed Watonga project in Oklahoma, the conclusion was similar for terrace and dune deposits (Johnson et al., 2013). In the end, the geologist and the developer need to come to their own conclusion. Since a typical geotechnical investigation for foundation design includes borings at each proposed turbine site, this mitigation method is effectively cost-free.
- Use construction methods. Most turbine spread foundations are relatively shallow (~2 to 3 m below grade at the base). Alternatively, the foundation can be placed on piles that are supported on rock below the karst zone. This may require additional investigation of the bedrock for the design of a pile foundation. Another option is to grout the underlying voids full to eliminate the potential for collapse. One advantage with grouting is that you can complete the detailed investigation to identify voids at the same time as the mitigation is being completed. Another possible construction method not encountered by these authors is to construct a foundation that bridges the risk zone. While a typical spread foundation is likely capable of bridging a small gap, the normal design process does not evaluate that possibility. Such a design consideration would need to be addressed on a case-by-case basis. Constructed mitigation adds hundreds of thousands of dollars to the cost of each turbine. Note that implementing constructed mitigation often means that detailed karst characterization is no longer required.

• **Don't build the project.** Developers typically have a pipeline of projects in development, so the best approach may be to move on to the next one. This means losing the investment to that point, so this is not done lightly. There is often great pressure to move forward despite the evidence of karst.

As noted previously, the earlier that karst risk can be identified and evaluated, the earlier the developer can factor the costs into the overall project budget. If karst is not identified until the construction phase, it is likely that the project cannot be stopped, and it may be very difficult for the project to ultimately be profitable.

Risk communication

The cost of failure of a single turbine can range from hundreds of thousands of dollars (slight but unacceptable differential settlement) to millions of dollars (extreme tilt to catastrophic collapse). It is therefore important to communicate the cost implications to the client as early in the project as possible. Part of dealing with the risk of karst is the apportionment of risk amongst the developer, the contractor, and the consultant/designer. Karst risk and risk apportionment is a very important conversation.

The financial commitment to the consultant/designer is often not significant enough to expect him/her to follow through with the level of investigation needed to completely characterize the risk or carry all the liability for a failure. A consultant/designer earns about \$5,000 per turbine, which does not offset the potential for a lost \$5 million turbine—especially when that risk is multiplied by tens or hundreds of turbines. Therefore, it is important to educate the client about karst and karst risk to the extent that the client can carry the bulk of the risk and can make informed decisions regarding the degree of risk and how extensive the risk characterization will be.

Effectively communicating with developers is critical. They want to know the exact location of the problem sites and may ask, "if there is a cave, what is the chance that a turbine will fail?" The developers typically don't understand karst and that, in many cases, the issue is cover collapse or soil piping, not cave collapse. It is also important to communicate the inherent uncertainty of karst risk and the cost of reducing the uncertainty. The consultant/designer has several options regarding liability:

- Ignore the issue. This is clearly unacceptable.
- Add a disclaimer. The disclaimer will state that it is impossible to completely know what is underground. This is a typical practice.
- Keep the investigation and evaluation of karst out of scope. In other words, pass the buck.
- Educate the client. Have the client make the major decisions and carry the majority of the risk. This is often resisted since it increases the client's workload and risk.

Project Examples

Table 1 summarizes the extent of investigation on projects where karst risk was evaluated mainly by the senior author. Following are some brief descriptions of a few of these sites.

North Central Iowa

There are sinkholes near, but not in, the project area. Drilling indicated that the bedrock is dolomitie (as opposed to limestone), with which karst development is linked in this region. Further, the drilling showed that sufficient soil cover exists over most of the site to mitigate risk (Figure 6) and did not find significant indications of karst development. After close consultation with the developer, this project was built.

Site Location	No. of turbines	Built?	Lit Search	Remote Sensing/ Lineament	Experts	Recon	Drill	Geo- physics	Comment
Arizona 1	62	No	Yes	Yes	Yes	NA	NA	NA	Project has not progressed past desk top phase
Arizona 2	62	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Developed area was reduced
lowa	79	Yes	Yes	NA	Yes	Yes	Yes	Yes	Glacial cover
Kansas	100	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Minnesota	~140	No	Yes	Yes	Yes	Yes	NA	Yes	Unbuilt as of spring 2012
New York	~90	No	Yes	Yes	Yes	Yes	NA	Yes	Karst ID'd early. Developer kept looking for a different answer
Ohio	175	Yes	Yes	No	Yes	Yes	Yes	Yes	Glacial cover
Oklahoma 1	129	Yes	Yes	No	No	No	Yes	Yes	Due to con- straints and schedule, investigation jumped right to field work
Oklahoma 2	~90	No	Yes	No	Yes	Yes	NA	NA	Dune cover Watonga
Pennsylvania	24	Yes	Yes	NA	Yes	Yes	Yes	Yes	Expensive mitigation
Texas 1	160	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Field investiga- tion was limited based on linea- ment analysis
Texas 2	242	Yes	Yes	Yes	No	Yes	No	Yes	
Texas 3	260	Yes	Yes	Yes	Yes		No	Yes	
Texas 4	28`	Yes	Yes	Yes	Yes	Yes	Yes	Yes	3-D geotechni- cal modeling

Table 1. Project Summaries. NA = Project did not advance



Figure 6. Cross section of wind project in North Central Iowa showing depth to bedrock. Thicker soil=less risk.

Southwest Pennsylvania

Literature review indicated, and site reconnaissance confirmed, that karst features were present in the area. Karst was associated with particular stratigraphic units, so areas of relative risk could be mapped (Figure 7). However, the site had other restrictions on where development could take place, and those limitations took precedence over karst risk. The developer took this project into construction before any subsurface investigation was completed. Once drilling began, numerous subsurface voids were found beneath most of the proposed turbine locations. In some places, multi-channel analysis of surface-wave geophysics was used to see if there were adjacent locations with reduced risk (Figure 8). However, the geophysics could not resolve fineenough detail, so multiple drill holes were completed at turbine locations that were at risk. Although not budgeted for, the developer ended up installing deep pile foundations at some sites and grouting voids in others, at great expense.

South Central Minnesota

The client was a contractor bidding on constructing the project. This is one of the most heavily karstified



Figure 7. Map showing relative risk for a wind farm in southwest Pennsylvania.



Figure 8. Cross section of shear wave velocity showing a sinkhole underlying a proposed wind turbine site in southwest Pennsylvania. Boring blow count decreased with depth.

areas of Minnesota (Figure 4). The contractor was advised to decline to bid on the project. To date, the project has not been built, although the developer continued to try to bring it to fruition for several years.

Northwest Oklahoma

Investigations in Blaine County, in northwestern Oklahoma, evaluated potential problems that gypsum karst may pose for the proposed Watonga Windpower Project. Gypsum beds of the Permian Blaine Formation underlie all parts of the Project Area, at depths ranging from 10 to 45 m below ground level. The Blaine is overlain by the Permian Dog Creek Shale and by unconsolidated Quaternary sands, clays, and gravels that may obscure karst features. Field studies, aerial-photo analysis, and a literature study showed that there is no direct evidence of gypsum karst in the project area. Placing wind turbines at sites where there was sufficient cover overlying the gypsum beds was appropriate risk mitigation: where gypsum is 25 m below ground level or deeper, the risk related to gypsum karst is low, and where gypsum beds are less than 25 m deep, risk was medium to high. A map (Figure 9) was prepared showing areas of low, medium, and high risk related to gypsum karst.



Figure 9. Risk categories at Watonga Windpower Project, based upon depth to the Shimer Gypsum at top of the Blaine Formation (Johnson et al., 2013)

Conclusions

Karst can lead to dramatic tilting and even toppling of a wind turbine. Subtle differential settlement of even 3 centimeters across a 15-meter-wide wind turbine foundation can cause the turbine to be out of tolerance, requiring remedial action. There are many tools available for evaluating karst risk at windpower developments, including low-cost desktop methods and field methods with widely ranging costs from reconnaissance to intensive drilling. The right tools at any given phase of a windpower development will be based on the site conditions, the funds available, and the riskmanagement discussions with the client.

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APPLICATION OF STABILITY CHARTS AND RELIABILITY CONCEPTS FOR SIMPLIFIED ANALYSIS OF A VOID IN SOIL OVERLYING KARST BEDROCK

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Abstract

The karst belt stretching from Alabama to New England is dominated by limestone/dolostone rocks which are observed to weather in-place forming a layer of residual clay soil above a highly weathered rock surface. As part of the natural weathering process, subterranean voids frequently develop in the overburden soil, which can lead to surface subsidence or collapse (sinkholes). Furthermore, construction activities can promote instability, especially where a portion of the soil overburden is removed. A rational method for addressing the potential for void collapse may involve the use of simplified charts to perform probabilistic analysis for likely ranges of void and soil conditions. This paper demonstrates the application of simplified stability charts and reliability concepts for evaluating the collapse potential of voids within the soil overlying the rock surface.

Introduction

Subterranean voids in the bedrock and in the overburden soil develop as part of the natural weathering process in the karst belt stretching from Alabama to New England, where the underlying limestone/dolostone rocks are observed to weather in-place forming a layer of residual clay soil above a highly weathered rock surface. A methodology for evaluating the static stability of discrete voids (i.e., caves) within shallow rock is presented by Siegel et al. (2001). Drumm and Yang, (2005) and Drumm et al. (2009) developed simplified charts for evaluating the static stability of a void within the soil overburden. However, there are aspects, such as the determination of representative void sizes and geometry, that present difficulties in characterizing the risk of void collapse. To overcome such difficulties, simplified stability charts may be combined with reliability concepts to characterize the risk of collapse of a void in the soil overlying the rock surface.

Simplified Charts for Soil Stability

Stability charts are widely used for the evaluation of soil slopes (Taylor, 1937; Bishop and Morgenstern, 1960) where the charts were developed in terms of the slope height and inclination, and the soil shear strength is expressed in terms of the soil cohesion intercept, c, and friction angle ϕ . These stability charts are typically presented in terms of a dimensionless stability number, N, which is often defined by Equation 1.

$$N = \frac{\gamma H}{c} \tag{1}$$

where N is a dimensionless stability number, γ is the unit weight of the soil, H is the height of the slope, and c is the cohesion component of the soil shear strength. Typically, the charts allow the potential for failure to be expressed in terms of a factor-of-safety (FS) or the ratio of the available soil strength to the strength required to maintain stability.

$$FS = \frac{c}{c_d} = \frac{\tan\phi}{\tan\phi_d} \tag{2}$$

where the parameters c_d and f_d are the corresponding values of the cohesion intercept and friction angle required to maintain equilibrium. Using some of the concepts originally applied to soil slopes, Drumm et al. (2009) prepared simplified charts for the evaluation of the stability of a void in the soil overlying the rock surface.

Stability Chart for Void in Soil

A subterranean void will be stable where the overlying soil is capable of re-distributing the stresses to competent material below. The ability of the soil to redistribute the stresses will depend on the void geometry, the soil thickness, the soil strength and the magnitude of the surcharge load, if present.

Characteristic Subsurface Profile

The characteristic subsurface profile in a highly weathered, clay-mantled karst terrain is described by Sowers (1996). From the ground surface, there is a blanket of soil that is composed of the insoluble portion of the karst bedrock. The upper residual soil is often stiff from overconsolidation as a result of exposure to multiple cycles of wetting and drying. With depth, the residual soil generally increases in water content and decreases in stiffness and strength. Competent karst bedrock (e.g., limestone) typically exhibits high strength but contains slots, caves, and other openings created by the solutioning process. Voids in the soil or "domes" are created as the soil ravels and/or migrates downward into slots, caves, and other openings in the underlying rock (Figure 1).

Finite Element Model

The dimensionless chart developed by Drumm et al. (2009) to evaluate the stability of a void in soil overlying karst bedrock is based on the results of finite element analyses. The analyses were conducted for a range of hypothetical soil properties and void geometries expressed in terms of the ratio of an assumed hemispherical void diameter (D) to soil overburden thickness above the void (h). The idealized model and terms used in the finite element analyses are shown in Figure 2.



Figure 1. Conceptual subsurface profile in karst with an enlarging void in the residual soil (Sowers, 1996).



Figure 2. Axisymmetric idealization of void in soil over rock (Drumm et al., 2009).

Assumptions made in the finite element analyses are summarized in the following:

- The geometric conditions around the void were approximated by a two-dimensional axisymmetric model, implying a hemispherical void of diameter D. The soil was assumed to be homogeneous except for analyses that assume a weaker soil layer with a thickness of 3D/4;
- 2. The stiffness of the rock was much greater (typically 10⁴ times) than that of the soil and, as a result, the rock was considered to provide a rigid support at the base of the soil. Therefore, the rock surface was represented by a fixed boundary in the model;
- 3. The lateral boundary of the finite element model was confirmed to have no effect on stability. The lateral extent (L) for the largest diameter was extended until it had negligible effect on stability. The results indicated that there was no boundary effect for an L/D>2.5 for h/D=0.5;
- The majority of the analyses were performed with a constant soil unit weight of 17.7 kN/ m³ (112.8 lb/ft³). However, the soil unit weight was incorporated into the dimensionless terms;
- 5. The soil strength was represented using the Mohr-Coulomb elastic-plastic model, which allows the soil to act as an elastic solid at stress levels less than the strength, and allows the soil to flow plastically at stress levels equal to the strength. The use of a Mohr-Coulomb failure criterion inherently assumes that the intermediate principle stress has no influence on the failure condition (Chen and Liu, 1990) and the failure is defined by Equation 3.

$$\tau = c + \sigma tan\varphi \quad {}_{(3)}$$

where strength parameters c and ϕ represent the cohesion intercept and angle of internal friction, respectively, and σ is the normal stress. A non-associative flow rule was assumed with a zero dilation angle ($\psi = 0$) which results in the soil experiencing zero volume change during yield. The tensile strength was assumed to be 20% of the undrained shear strength values (c_u). This assumption, while somewhat arbitrary, allows for a variation in tensile strength in proportion to cu while maintaining the dimensionless stability factors;

6. The elastic modulus of the soil (E) was assumed to be 22 MPa (4.6 x 105 psf). Although the stability is not sensitive to the elastic modulus provided it is a constant, this value is consistent with published correlations with the undrained shear strength (Das, 1999).

$$E = 440c_u \tag{4}$$

where c_u is the initial value of undrained shear strength used in the analysis. The deformation field and the surface subsidence were not considered;

- 7. The Poisson's ratio was assumed to be 0.3 which is consistent with published values for a variety of soil types (Bowles, 1988). In general, the results of the evaluation are somewhat sensitive to Poisson's ratio;
- 8. The initial field stresses were represented by restraining the soil around the void while applying the gravitational force with a stress ratio K_o according to Equation 5

$$K_o = 1 - \sin\varphi' \tag{5}$$

after which the soil around the void was released allowing deformation, and;

9. The water table is assumed to remain constant at a position below the top of the rock surface. This assumption results in the greatest effective stress for any of the conditions considered. Enlargement of the void due to soil loss is neglected and seepage effects on stability are not considered.

Determination of Collapse Load

The dimensionless ratio h/D was used to define the subsurface geometry where h is the minimum soil thickness over the void () and D is the void diameter (Figure 2).

The dimensionless stability number (N_c) was determined by applying the shear strength reduction (SSR) method proposed by Zheng et al. (2006). In the SSR method, which is widely used in both soil and rock engineering (Griffiths and Lane, 1999; Swan and Seo, 1999), the strength parameters of the model are reduced by a strength reduction factor (SRF), such that

$$\tau = \frac{c + \sigma \tan \varphi}{\text{SRF}} \tag{6}$$

the finite element analysis is conducted with incrementally increasing values of SRF until the analysis does not converge to equilibrium. This determines the critical SRF and represents a factor-of-safety of unity. The critical SRF can be used to calculate the critical strength and N_c .

Soil Friction Angle

Analysis using only undrained shear strength may be considered representative of short term conditions. To extend the analysis to long term (or effective stress) conditions, the stability was also evaluated using the similar methodology with a value of . The approach used for was repeated to determine the value of c corresponding to a convergent solution for values of with the SRF applied the tan ' and the initial stress ratio following Eq. (6). The stability chart is presented in Figure 3.

Inverted Strength Profile

Rather than having a profile where the shear strength increases with depth (as is the case in most geologic settings), karst often exhibits a soft zone above the rock surface. This is often referred to as an inverted residual strength profile (Sowers, 1996). To consider the inverted strength profile, analyses were performed for undrained conditions ($\varphi = 0$) with the lower 3D/4 portion of the soil profile assigned a reduced undrained shear strength (c*).

$$c^* = \alpha c \tag{7}$$

where c^* is the reduced undrained shear strength for the bottom 3D/4 part of the soil layer; c is the undrained shear strength of the soil; and α is the inverted strength factor. Figure 3 includes the stability numbers for undrained conditions with inverted strength factors of 0.25, 0.5, and 1.0.

Functional Form of Stability Chart

To allow direct use of the stability chart shown in Figure 3, a linear function was fitted to the curves using the following form.

$$N_{c\phi} = a (h/D)^3 - b(h/D)^2 + c(h/D) + d$$
(8)

where a, b, c and d are constants determined by regression analyses. The values of constants a, b, c, and d for a range of values of ϕ and α are presented in Table 1.

Reliability Concepts

Reliability concepts provide a useful framework for analysis where there is uncertainty in the parameters involved (Harr, 1987; Whitman, 1996). For application of the stability chart presented herein, it is proposed to incorporate the approach proposed by Duncan (2000) which allows an assessment of the reliability of the factor-of-safety and calculation of the probability of collapse using the following steps.

1. Estimate the standard deviations of the parameters involved. Duncan (2000) suggests applying the "threesigma rule" which makes use of the fact that 99.73% of all values of a normally distributed parameter fall within three standard deviations of the average. The standard deviation is computed using the Equation 9.

$$\sigma = \frac{HCV - LCV}{6} \tag{9}$$

where HCV is the highest conceivable value and LCV is the lowest conceivable value.

- 2. Use the Taylor series technique (Wolff, 1994; U.S. Army Corps of Engineers, 1997 and 1998) to estimate the standard deviation and coefficient of variation of the factor-of-safety.
- 3. Determine the "probability of failure" and the reliability of the factor-of-safety based on a lognormal distribution of values. Duncan (2000) presents a table that summarizes the mathematical results necessary to apply a lognormal distribution.

Table 1. Constants and r² values for curves in Figure 3 (Drumm et al., 2009).

Constants a, b, c and d along with r2						
		а	b	с	D	r2
	0	0.0013	0.0766	1.9944	1.8914	0.9982
Φ(°)	10	0.0004	0.0353	2.0744	0.6521	0.9990
	20	-0.0008	-0.0101	2.6131	0.6484	0.9994
	30	-0.0005	-0.0033	3.2346	0.6168	0.9987
α	1.0	0.0013	0.0766	1.9944	1.8914	0.9982
Φ=0	0.5	0.0014	0.0826	1.6923	0.6220	0.9959
	0.25	0.0006	0.0400	0.8339	0.3145	0.9954



Figure 3. Stability chart for estimating Nc, for a void in soil overlying rock (Drumm et al., 2009).

Case History: Landfill in Karst Terrain

The simplified stability charts and reliability concepts presented herein were used to evaluate the collapse potential of voids within the soil during the permitting activities for a landfill in a karst region in northeastern Alabama. The project information is summarized in the following paragraphs.

Geologic and Subsurface Conditions

Published maps show that site is located within the Appalachian Plateau (Hunt, 1967) and that the bedrock is light gray and light brown, locally sandy dolostone, dolomitic limestone and limestone of the Knox Group Undifferentiated.

The geotechnical exploration consisted of soil test borings, air-track probes and multi-electrode electrical resistivity. On the basis of the exploration results, the subsurface conditions are characterized by a thick layer of residual soil consisting of very stiff (average SPT N of 28), sandy clays and silts with interbedded seams of clayey gravel (chert) and sand. The soil thickness ranged from approximately 5 $\frac{1}{2}$ to 30 $\frac{1}{2}$ m (18 $\frac{1}{2}$ to 100 feet). There was a slight decrease in SPT N from 20 to 50 ft below the ground surface.

The soil strength was characterized based on the results of consolidated-isotropically, undrained compression triaxial tests that were performed on soil samples obtained in similar geologic and geotechnical conditions. The strength test results are summarized in Figures 4 (total stress or undrained strength) and 5 (effective stress or drained strength).

Multi-electrode electrical testing was performed in an effort to identify landfill areas that may be underlain



by a void within the soil. The method involves passing direct current through the earth between two electrodes and measuring the resulting voltage drop between an additional pair of electrodes (Roth and Nyquist, 2003). A typical resistivity profile is presented in Figure 6. Sharp contrasts or "anomalies" within the resistivity profile were considered potential subterranean voids.

Void and Soil Parameters

No voids were encountered within the test borings, including those that were drilled at "anomalies" (extremely high resistivity values or extremely low resistivity values) interpreted from the multi-electrode electrical resistivity testing. Considering the results of the geotechnical exploration and published data of doline diameter (Newton and Tanner, 1986; Martin, 1995; Qubain et al., 1995, Abdulla and Mollah, 1997; Mishu et al., 1997; Smith, 1997; and Thomas and Roth, 1997), a void diameter of 6 feet was considered to be a realistic, conservative assumption. It was anticipated that voids having a diameter greater than 6 feet, if present, would be detected during the resistivity testing and borings that target resistivity anomalies. This would allow application of corrective actions (e.g., cap grouting) to significant voids. Optionally, the range of void diameter (or any other variable) could have been explicitly considered in the reliability analysis.

The soil unit weight ranged from 18.0 to 19.9 kN/m3 (114.5 to 126.5 pcf) and averaged 18.9 kN/m3 (120.5 pcf). The soil thickness (i.e., the overburden height (h) ranged from 7.8 to 22.5 m (25.6 to 73.8 feet) and averaged 15.2 m (49.7 feet).

The undrained shear strength ranged from 40.2 to 110.6 kPa (840 psf to 2310 psf) and averaged 74.2 kPa (1550 psf). An inverted strength factor (α) of 0.6 was applied for undrained conditions. The effective friction angle ranged from 20.4 to 20.9 degrees and averaged 20.6 degrees. The effective cohesion ranged from 15.1 to 54.6 kPa (324 to 1141 psf) and averaged 35.1 kPa (733 psf).

Probability of Void Collapse

Following the Duncan approach (2000), the Taylor Series was used to compute the probability of void collapse for the conditions at the Alabama landfill. The method requires that factors-of-safety be determined where each parameter is individually increased and decreased one standard deviation (s.d.) from its "most likely value". A summary of factorsof-safety is presented in Table 2.The factors-ofsafety for the most likely values (MLV) are 2.74 and 2.79 for total stress conditions and effective stress conditions, respectively. The standard deviations of the calculated factors-of-safety are 1.46 and 1.57, respectively. The coefficient of variation (VF) for the each factor-of-safety may be determined using Equation 10.

$$V_F = \frac{s.d.F}{FOS_{MLV}} \tag{10}$$

The computed VF values are 53.3% (total stress conditions) and 56.2% (effective stress conditions). The lognormal reliability index (β_{LN}) values are calculated using Equation 11.

$$B_{LN} = \frac{\ln(\frac{FOS_{MLV}}{\sqrt{1+V_F^2}})}{\sqrt{\ln(1+V_F^2)}}$$
(11)



Figure 4. Total stress strength data (1 ksf = 47.88 kPa).



Figure 5. Effective stress strength data (1 ksf = 47.88 kPa).



Figure 6. Typical resistivity profile (1 ft = 0.305 m) (Examples of "anomalies" noted by red circles).

and the probability of void collapse (P_f) can be calculated using Equation 12.

$$P_F = 1 - \beta_{LN} \quad (12)$$

The calculated probabilities of collapse are 3.9% (total stress conditions) and 4.5% (effective stress conditions). According to Vick (2002), these values correspond to conditions where void collapse is between "almost impossible" to "very improbable".

Conclusions

Subterranean voids in the overburden soil develop as part of the natural weathering process in karst terrain. Even in cases where the soil strength is well characterized, there is often uncertainty with respect to the size and geometry of the potential subterranean voids. Furthermore, construction activities can promote instability, especially where a portion of the soil overburden is removed. A rational method for addressing the potential for void collapse involves the use of simplified charts by

Table 2. Summary of factors-of-safety.

Total Stress Conditions							
Variable	с	h	g				
FOS (+s.d.)	4.09	2.21	2.61				
FOS (-s.d.)	1.49	3.51	2.89				
Δ FOS	2.60	1.30	0.28				
Effective Stress Conditions							
Variable	c'	φ'	h	γ			
FOS (+s.d.)	4.35	2.81	2.74	2.66			
FOS (-s.d.)	1.23	2.78	2.87	2.94			
ΔFOS	3.12	0.03	0.13	0.28			

Drumm et al. (2009) to perform probabilistic analysis for likely ranges of void and soil conditions. In such a way, the potential for void collapse may be described in both numerically (i.e., probability of collapse) and verbally (e.g., very improbable, almost improbable, very unlikely...). The example presented herein represents a snapshot of a hypothetical void under static condition. It is important to note that multiple analyses may be required to fully characterize the risk of void collapse.

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IF IT'S WEIGHT OF HAMMER CONDITIONS, IT MUST BE A SINKHOLE?

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Abstract

In a Florida sinkhole investigation, many people (engineers, geologists, lawyers, insurance agents, public adjusters and media) interpret weight of hammer (WH) and weight of rod (WR) as a void, and by association, a sinkhole (author is a Florida Neutral Evaluator). This causes some to allege the site contains a sinkhole damaged home--damage that is likely related to poor maintenance, construction or design issues. The concept of finding WH/WR conditions has resulted in many sinkhole investigations becoming a gamble with the homeowner or their representative wagering against the insurance company that there will be WH/WR conditions found and therefore a sinkhole present under the building likely giving the homeowner a payoff for a sinkhole. The rules for the game are mandated in Chapter

§726.706 of the Florida Statute that ultimately results in who can be more successful in convincing a jury that a given set of conditions is or is not a sinkhole. Since the WH/WR conditions plays a significant role in sinkhole determinations, this paper will discuss the causes of WH/ WR conditions and its meaning in terms of stress that develops during soil sampling. It will further consider the distribution of stress and the potential for these conditions to influence a structure at the ground surface. Conversely, it will also discuss the factors necessary for these conditions to impact a structure and other conditions that can give false indications of sinkhole activity. Also provided are examples of case studies where critical subsurface conditions were resolved using considerations discussed in this manuscript.

Introduction

In sinkhole investigations in west-central Florida where overburden conditions generally consist of fine sandy soils, it is not uncommon to see reports written by professional engineers and geologists with the assertion that because weight of hammer (WH) or weight of rod (WR) conditions are present it implies a void is present below the ground surface and hence sinkhole conditions exist. This hasty conclusion does not consider the high stresses imparted to the soil by the drill string and the inability of loose soil to support a void at relatively shallow depths below the ground surface (Zisman, 2003, 2005). This paper will discuss the formation and testing of these conditions, their meaning in the context of sinkhole formation and suggested steps for determining sinkhole presence. An example of this condition as it occurred in an actual sinkhole investigation will also be discussed.

A further factor in the WH/WR condition used in the identification of sinkholes is the nature of the overburden materials generally occurring in west-central Florida. In this area fine sandy soils predominate and cover the relatively weak Cenozoic carbonates of Florida. These sediments consist predominantly of residual soils known to decrease in strength with increasing depth as opposed to transported soils which increase in strength with increasing depth (Sowers, 1996). This phenomenon is discussed in more detail in Section 6. The important consideration is that WH/WR conditions are not likely the result of soil arching but the result of soft zones normally found in residual soils. Determination of whether soil arching has affected the subsurface is found from the characteristics of the underlying soil or rock material. If conduits consisting of fractures and fissures are present in the underlying rock then one cannot rule out the possibility of soil arching. This is discussed in greater detail in Section 3.

Also discussed are the requirements in the Florida statute that aid in the determination of sinkhole activity. Examples are given through the use of soil profiles showing conditions that are not indicative of sinkhole formation and the reasons for these conclusions.

Stress Associated with SPT Sampling

The Standard Penetration Test (SPT) adopted by ASTM in Test Method D1586 is widely used in sinkhole investigations to determine the consistency and type of material occurring at depth below the ground surface. Unfortunately, when no sample or "N-value" is obtained and the drill string drops under its own weight (WR) or under the additional weight of the hammer (WH), it is difficult to predict what has caused this condition unless one considers the stresses that exist at the end of the drill string in relation to insitu stress.

First, consider the stresses that are present at the tip of the drill string during SPT sampling as shown in Figure 1. These stresses are based on the following assumptions: 1) buoyant conditions are present with a buoyant soil weight of 55 pcf (881 kgs/m3), 2) surface loading from a typical residential home is 2,300 psf (11,230 kgs/m²) and 3) A-rods weigh 31 pounds (14 kgs) per 10 foot (3 m) length of drill rod, the difference in weight between the drill rod and the 2-foot (0.6 m) sampler was not considered. Shown in this figure is a plot of buoyant drill string weight with depth together with a plot of the buoyant soil weight of the column of soil replaced by the drill string with depth. It is apparent that the drill string weight exceeds the soil weight at all depth intervals and that the rate of increase in the drill string weight is greater than the rate of increase of soil weight with depth. So as we drill deeper, we exceed the overburden pressure with the drill string weight by a factor of over 2, which accentuates loose or soft soil zones that cannot support the increasing weight of the drill string resulting WH/WR conditions.

Another consideration is the stresses at the tip of the sample spoon are very large, for example, at 20 feet (6.1 meters) the stress exerted by the sampler on the soil is 207 psi (14.3 bar), at 40 feet (12.2 meters) it is 405 psi (27.9 bar) and at 80 feet (24.4 meters) it is 800 psi (55.2 bar). Compare these stresses to the stress a women, wearing high heel shoes, places on asphalt that has been warmed by the sun. If the heel is one square inch in area, and a woman places 100 pounds (45.4 kg) on each leg they will apply a pressure of 100 psi (6.9 bars) enough stress to easily deform the asphalt. However, when we subject the soil, at depth, to stresses of 200 psi (13.8 bars) to 800 psi (55.2 bars) (see Figure 1) some consider a void present if the soil at that depth will not support the drill string.

For the WR conditions, many consultants only report the condition is present without providing information on the rate of rod fall. Depending on the type of soils, the rate of rod fall can be useful in determining the type and



Figure 1. Comparison of Soil Weight with Weight and Stress of Drill String.

consistency of the material. Consider if there is a gradual fall of the rods, one may conclude that a zone of soft clay or sand is present, depending on the material in the cuttings found in the wash water. The point is that many boring logs do not contain sufficient information to accurately provide a picture of what occurred during the drilling of the boring and consultants simply conclude the worst in the absence of this information.

We must also consider the conditions that can occur in some of the soft soils that are commonly susceptible to remolding from the removal and insertion of the drill string. Rapid movement of the drill string can cause extreme changes in the state of stress at the sampling depth resulting in further disturbance and consequent loss in soil strength.

Florida Statute Requirements for a Sinkhole

The Florida statute in §627.706 has established that "sinkhole activity" is present when: "settlement or systematic weakening of the earth supporting the covered building only if the settlement or systematic weakening results from contemporaneous movement or raveling of soils, sediments, or rock materials into subterranean voids created by the effect of water on a limestone or similar rock formation." (Florida Statute 627.706) Figure 2 provides a further explanation of the statue.

From Figure 2, it is seen that two conditions must be present: dissolution of the limestone and the overburden ("supporting material") must be affected for sinkhole activity to exist (see Steps 1 & 2 in Figure 2). Further, in the author's assessment, the use of the words: "earth supporting the covered building" implies that the building must be damaged in the area where the soil has been "weakened". Therefore, it is concluded that consultants must find damage in the structure related to systematic weakening of the soil, separate from damage related to poor construction and maintenance to declare a sinkhole is present. The determination of the cause of building damage requires a thorough forensic investigation of soil conditions and, in particular, structural conditions to distinguish between damage from sinkhole activity verses damage from design, construction and maintenance deficiencies.

Steps

Statute

Subsurface



<u>§627.706</u> (d) "Sinkhole activity" means settlement or systematic weakening of the earth supporting the covered building only if the settlement or systematic weakening results from contemporaneous movement or raveling of soils, sediments, or rock materials into subterranean voids created by the effect of water on a limestone or similar rock formation.

¹ This chart is appropriate for most conditions



From this discussion it is seen that there is no definitive measure in the statute as to what constitutes sinkhole activity; there is much left to interpretation. Therefore, the interpretation of the cause of WH and WR conditions becomes a very critical aspect of a sinkhole investigation.

Boring Logs

The information contained in the boring logs for a site investigation is generally the most useful data developed at the site. Overall, when we consider that the boring logs cover less than 1% of the site area (the area sampled by four borings compared to the area under the structure-Zisman, 2003, 2005) and information from geophysical methods is limited in depth of coverage, we then must place great emphasis on information from borings. In sites where ground penetrating radar (GPR) is the only geophysical method in use, it is not uncommon to find GPR data limited to depths of 10 to 15 feet (3.0 to 4.6 meters) below the ground surface. Although good radar penetration is achieved in dry sandy soils, the penetration in clay-laden soils and soils with high electrical conductivity is sometimes only a few centimeters. Resistivity is not subject to all of the limitations of GPR but its depth of penetration is limited to about 25% of the length of the traverse, which presents a problem with depth of penetration at many residential and commercial sites with limited property. The marginal amount of data that may be obtained by geophysical methods places additional emphasis on developing complete information in the boring logs.

Because of the complexity of subsurface conditions in karst terrains, we must carefully analyze subsurface conditions and not oversimplify them by only using the abbreviations WR and WH. Boring logs should contain a complete description of the circumstances under which these conditions occurred. The boring log should provide a record of not only the soil material found but also a detailed discussion of what occurred while sampling the soil and rock material. This information is typically absent from many consultants' reports. For these reasons a good deal of effort must be placed into analyzing the origin of all building damage and relating this damage to potential subsurface conditions by considering the building as a giant test cell and analyzing building damage to explain its source relative to sinkhole causes or construction/design/maintenance causes.

Geologic Conditions

When conducting a sinkhole investigation in westcentral Florida, we must not lose sight that, for the most part, we are analyzing Coastal Plain sediments deposited in diverse shallow marine environments. The geology of Florida is composed of strata formed during three geologic periods Holocene, Pleistocene, and Pliocene. During this time sands containing varying amounts of silt and clay were deposited on the bottom of shallow seas that existed during interglacial time when sea levels were higher than present (Kuhns, et al, 1987). During this time the great expanses of limestone that underlie most of the State of Florida were formed in these shallow seas. Most of the limestones contain impurities that resulted from depositional conditions during the formation of the limestone in the shallow marine environment. For example, during deposition, the limestone was subjected to erosion from streams and offshore currents that resulted in inclusions of sediments that now serve as pervious conduits that facilitate weathering. Moreover, the clastic components of the limestone mass vary, thus creating areas within the indurated mass that are more permeable, and therefore more prone to dissolution.

An important factor in the discussion of sinkhole development is to consider the time required for the dissolution of limestone. The rate of limestone dissolution is from 5 to 200 mm per 1,000 years. For the climate in eastern U.S. and Western Europe, the rate is between 25 and 40 mm per 1,000 years (Sowers, 1996).

Geotechnical Conditions Related to the Overburden

The overburden covering the limestone may consist of transported or residual soils. In transported soils "N-values" generally increase with increasing depth because the oldest material is on the bottom of the profile and has had the longest time to consolidate under the weight of the overlying soil. In residual soils overlying limestone, the opposite is generally true with the youngest soil occurring at the bottom of the section. In this case the "N-value" is found to be uniform or slightly decreasing with increasing depth until at a short distance above the limestone surface the soil may become softer with increasing depth as reflected in the SPT value (Sowers). The lower SPT value may result from erosion of soil raveling into solution slots or discontinuities in the limestone, which results from depositional features. The progression of these zones is generally very slow

and their presence is normally investigated by the use of geophysical methods or may be detected by trends in the SPT borings drilled for the investigation. Because of limits in the depth of penetration of GPR data particularly when clayey soils are present, it is recommended that both GPR (ground penetrating radar) and ERI (electrical resistivity imaging) methods of geophysical profiling be used in the sinkhole investigation.

In GPR investigations, a 250 mHz antenna is commonly used outdoors and the higher frequency 500 mHz antenna is used inside the building to determine if settlement has occurred under the building slab. ERI traverses can provide information where GPR has limited penetration; however, ERI is limited to a depth of approximately 25% of the traverse length. In many residential and commercial sites where property is limited this presents a significant problem.

Sinkhole Determination

In analyzing subsurface conditions, there are a number of other key conditions used to judge the presence of sinkhole activity (Zisman, 2003, 2005). For example, drill string excursions, loss of circulation during drilling, absence of a confining clay layer above the limestone, relief of the limestone surface, associate damage in the home etc. A sufficient number of these conditions coupled with an understanding of the site geology need to be present before sinkhole activity can be established.

From what has been discussed, it is seen how easily the investigation can be influenced by the results of WH or WR conditions in a boring. These conditions may result from a boring intercepting a raveling zone at a depth substantially below the ground surface where this zone will not affect the structure in the foreseeable future. Depending on site condition it is common for some to ignore features occurring at depths greater than about 60 to 80 feet (18.3 to 24.4 meters) depending on the damage in the building (Zisman, 2003). To determine the importance of the WR/WH condition one needs to consider the presence of distress in the home and determine if there is a correlation between distress in the building and subsurface conditions or if distress is related to structural deficiencies. For this reason it is important to locate one or more borings adjacent to an area where distress is found in the structure.

Another consideration in the evaluation of subsurface conditions, particularly when WH and WR conditions are present, is the investigator should perform an analysis of settlement at each boring location and determine the amount of settlement that will occur at each location. The magnitude of settlement determined at each boring location should be used to establish the influence of subsurface conditions on overall building performance during the past and future life of the structure. If the analysis of settlement at each boring location results in essentially the same magnitude of settlement, this becomes a compelling factor in finding no sinkhole, provided that other considerations are not at play such as building damage that results from maintenance/construction/design factors (Zisman, 2010).

Case Studies Case Study No. 1

Figure 3 provides a soil profile for a site where one consultant found sinkhole activity present while another concluded no sinkhole activity was present (the dashed lines on the figure define the limits of a loose soil layer). From analysis of subsurface conditions shown in this profile plus the data determined from other sources, it was concluded that sinkhole conditions are not present. The following summarizes the reasons for this conclusion:

1) no evidence of loss of circulation was found in the five rotary-wash soil borings drilled at the site, 2) no correlation can be made to locations of exterior distress in the building and adverse subsurface conditions, 3) there is no evidence of movement of soil or raveling of soil into voids created by effects of water on limestone therefore there is no effect on the overburden (see Figure 2), 3) stucco damage found in the building is the result of construction deficiencies and poor maintenance, 4) all borings generally show similar lithologic conditions, 5) loose material found in the borings is a reflection of depositional conditions, 6) the general decrease in "N-value" with increasing depth is to be expected in residual overburden soils as opposed to the increasing "N-value" with increasing depth that occurs in transported soils, and 7) the site is located near the east coast of Florida in an area not known for sinkhole activity.

Case Study No. 2

Figure 4 shows typical subsurface conditions at a site in westcentral Florida. No sinkhole activity was found at the site. This conclusion was based upon several factors as follows:



Figure 3. Case study No. 1—a Site Near the East Coast of Florida (red indicates N-values less than or equal to 4, depth in feet).



Figure 4. Case study No. 2—a Site in West-Central Florida (red indicates N-values less than or equal to 4, depth in feet).

1) the loose zone found in boring B-2, approximately 75 feet (22.9 meters) bls (below land surface), is associated with localized weathering or depositional conditions often found in this region and has had no effect on overburden conditions, 2) the soft zone in boring B-2 lies at depths beyond structural influence, 3) no abrupt disruption of stratigraphy was observed, 4) loss of drilling fluid circulation, found in the borings, is a common occurrence in karst areas, and is considered to be related to localized increases in permeability associated with fractures and depositional features at or near the limestone surface, 5) the 55 foot (16.8 meter) difference in the depth to rock across the property is not uncommon in karst terrains and is not necessarily associated with sinkhole activity, 6) there is no focus to the damage found in the home and all damage appears to result from construction issues, and 7) there is no evidence of movement of soil or raveling of soil into voids created by the effects of water on limestone therefore there is no effect on the overburden (see Figure 2).

Conclusions and Recommendations

The following is a summary of some of the conclusions made in this paper:

- 1. It is misleading to consider that the occurrence of WH conditions in a boring as a void. Since the stresses imposed at the tip of the sample spoon are higher than insitu conditions, one must conclude that soil material at the bottom of the drill string has at least enough strength to support the weight of the drill string and therefore, WH conditions does not represent a void.
- 2. WR conditions may or may not represent a void depending on the speed with which the rods fall. If the drill undergoes a slow gradual drop, one may be compelled to consider that there is some material at the bottom of the hole that can partially support the weight of the rods. However, if a rapid fall of the rods is found than one can conclude that void may be present.
- 3. More information should be placed on the boring logs, in particular, a record of the rate of fall of the drill string when WR and WH conditions are present.
- 4. Determine if a correlation is present between the location of building damage and location of subsurface conditions. A very important part of a sinkhole investigation is determining the

mechanisms causing damage and determining if this damage can be caused by subsurface conditions.

- 5. Explain the origin of all distress found in the building. This may require an evaluation of the structural integrity of roof trusses, structural connections and modeling all distress to determine the overall building movement.
- 6. The Florida Sinkhole Statute requires that overburden material supporting the structure should be weakened or settled as a result of movement of the soil into pervious conduits in the limestone.
- 7. An analysis of the potential settlement that may occur at each boring location should be performed to determine if differential settlement can occur from the conditions determined in the investigation. Since borings may not be located in the exact areas of building damage, engineering judgment should be applied to assure all assumptions are reasonable.

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EXPLORATORY GROUTING OF A SUBSURFACE DETENTION/INFILTRATION SYSTEM

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Abstract

In 2007, a geotechnical investigation was performed for a student center at a New Jersey college. Even after reviewing the results of that study, the Municipality recommended incorporating a subsurface detention/ infiltration system below the parking lot adjacent to the student center.

The project area is underlain by solution-prone Beekmantown Formation dolomites. Mapped just to the northwest is the conformable solution-prone Allentown Dolomite. The Allentown likely dips shallowly below the Beekmantown. This local suite of carbonate bedrock lies within a fault-bounded block of these Cambro-Ordovician rocks.

Sinkholes formed beneath and adjacent to the basin and parking area and remediation was attempted by others. Repairs reportedly included the removal of basin fill materials, low-mobility grouting and stone backfill placed in subsurface voids. Shortly thereafter, more sinkholes opened, some within the area remediated.

Technical problems at the site included a lack of reliable subsurface information; the basin functioning in a manner that allowed infiltration; having the likely need to vary the grout and delivery procedures based upon encountered conditions and probe hole locations in relation to the basin; the need to remediate solution features trending beyond the original area of interest; and the possibility of unrecognized solution features outside the area of interest and below the student center.

These potential problems were brought to the attention of the current college administration. They quickly recognized the concerns and requested a different geotechnical firm to develop specifications for remediation and to help in choosing a suitable contractor.

To address the concerns, site-mixed grout using cement, water, mason sand and bentonite, in varying proportions, delivered under varying pressures, and using two different grout mixing methods was deemed the most appropriate remedial alternate. During the field operations, liaison and cooperation between the grouting engineers, the grout crew, and the college administration and maintenance personnel provided useful insight and support.

The various procedures used and the bases for their use are discussed in this paper. A total of 41 probe holes were drilled where a total of 157 m³ (205 cubic yards) of grout was placed. Voids as large as $5\frac{1}{2}$ m (18 feet) in vertical extent were encountered and a maximum of 18.6 m³ (24.3 cubic yards) of grout were pumped into any single probe hole. Subsurface connection between probe holes was evidenced as grout was seen to travel at least 3 m (10 feet) laterally.

Introduction

A college in north-central New Jersey constructed a large, multi-purpose student center that includes a performing arts center, student cafeteria, radio station and administrative offices. The construction included a large, detention/infiltration system to handle the storm water from the structures and additional parking. The college hired a development company that had previously managed construction at the school to spearhead the new project. In the authors' opinion, after reviewing the available data, the geotechnical engineers employed for the planned construction did not seem to understand the difficulties that could result from founding such facilities atop karst terrane. Additionally, the municipal engineer exacerbated the problem by requiring a below-grade stormwater detention and infiltration basin under a portion of new parking area to be constructed. The basin is about 37 by 12.2 m (120 by 40 feet) in plan dimension and the bottom is about 3 m (10 feet) below the parking lot surface. The stormwater system consists of five rows of 1.2-meter (48-inch) diameter, perforated HDPE chambers surrounded by 19-mm (³/₄-inch) clean, washed, crushed stone with a geotextile filter placed between the existing subgrade and the system; typical construction for such systems in the northeastern U.S. The parking lot is subject to vehicle loads from passenger cars and heavy delivery trucks.

After one year of use, sinkholes formed within the parking lot and adjacent landscaped areas. Initially, crushed stone backfill was used in an effort to stabilize the sinkholes and preserve infiltration. As the sinkholes continued to grow in size and number despite repairs, the construction contractors removed approximately a third of the entire system, saving the stormwater filter structures (installed to prevent debris from compromising the system) and the HDPE chambers. Stone fill, graded rock, geogrid and geotextile (filter fabric), along with a very limited program of low-mobility grouting were used to remediate the sinkholes affecting the basin area and the system was reinstalled and the parking lot replaced.

Geology

The site lies upon a fault-bounded block of the Cambro-Ordovician-aged Lower Beekmantown Formation rocks (Figure 1). The Lower Beekmantown Formation is described by the New Jersey Geological Survey (NJGS) as "very thin to thick-bedded, interbedded dolomite and minor limestone. Upper beds are light-olive-gray to dark-gray, fine- to medium-grained, thin- to thick-bedded dolomite. Middle part is olive-gray-, light-brown-, or dark-yellowishorange- weathering, dark-gray, aphanitic to fine-grained, laminated to medium-bedded dolomite and light-gray to light-bluish-gray-weathering, medium-dark- to darkgray, fine-grained, thin- to medium-bedded limestone. The limestone beds grade laterally and down section into medium- gray, fine-grained dolomite. Lower beds consist of medium-light- to dark-gray, aphanitic to coarse-grained, laminated to medium-bedded, locally slightly fetid dolomite having thin black chert beds, quartz-sand laminae, and oolites. Lenses of light-gray, very coarse to coarse-grained dolomite and floating quartz sand grains and quartz-sand



Figure 1. Bedrock geology map.

stringers at base of sequence. Lower contact placed at top of distinctive medium-gray quartzite. Unit is about 183 m (600 ft) thick." (NJGS, 2000).

The quality of the NJGS work in many areas of the State, with its many variations in structure, material types and tectonic history is of great value to geotechnical consultants. In this instance, comparing good test boring data to the various NJGS descriptions of the Lower Beekmantown Formation and Allentown Dolomite would have allowed a better understanding of the site subsurface.

The basin site is mapped as being very close to a formational contact with the Allentown Dolomite, which likely dips below the site at a relatively shallow depth.

In our experience, the Lower Beekmantown and Allentown have proven solution-prone wherever encountered in New Jersey and Pennsylvania.

The existence of nearby faulting is significant as much dissolution in this region is generally related to stress conditions and resultant fracturing. The southeasterly dip to the carbonates in the locale is also of significance as solutioning varies with differences in the bedrock constituents affecting cavity formation along fracture trends as well as bedding.

The Conclusions and Recommendation section of the 2007 geotechnical report starts by stating "Neither the borings

nor our observations revealed any evidence of solutioning, subsidence, sinkhole or other karst topographic features that preclude site development." The senior author's review of the drilling logs indicate that of the 20 borings drilled deeper than 2.4 m (8 feet) below grade, 18 showed some evidence of karst features such as drilling fluid losses, soft soils atop the bedrock surface, variations in rock depth over short horizontal distances, open fractures and seams, and the redirection of the drill string from pinnacles.

Stormwater Detention/Infiltration

Subsurface infiltration of storm water after some form of sediment removal is generally considered mandatory (with some exceptions) in New Jersey. Originally, the design proposed a surface detention basin, presumably with sufficient infiltration to recharge the local groundwater regime with an equivalent amount of precipitation that would be lost to impermeable cover (a New Jersey Department of Environmental Protection [NJDEP] requirement for new construction). During the municipal review process, the Planning Board advised the college that subsurface stormwater detention/ infiltration was more desirable. In fact, the geotechnical consultant's report provided two short paragraphs of recommendations for a "subsurface stormwater disposal system" without noting any concerns for the carbonate bedrock below the basin area.

In addition, the new construction included several openbottomed stormwater inlet/dry well basins. Other such basins had been installed throughout the campus during earlier construction; their age evident by their brick and mortar construction.

So essentially, the college went ahead with the various engineering recommendations without any warning from their professionals as to the problems that could exist as a result of the karstic subsurface.

Sinkhole Occurrence and Remediations

Depressions and two sinkholes began to form in and near the parking lot surface in the fall of 2010 (Figure 2). The first step proposed to the college by the original consultants/designers was to video the length of the five rows of HDPE chambers. The video survey reported pipe/chamber conditions ranging from "good condition" to "punctured" and "cracked". The next step was to excavate the northwestern corner of the system. After inspecting the excavated area, one of the solutions offered



Figure 2. Sinkholes in the subsurface stormwater system.

by the original geotechnical engineering firm was to fill the sinkholes with a "cementious/fly ash flowable fill or lean concrete". In the authors experience, conventional "flowable fill" does not flow well, usually does not have sufficient cement to bond the aggregate, and shrinkage results in passages that allow water inflow and erosion into open subsurface cavities/fractures

An additional recommendation was to fill sinkhole throats with a "graded rock porous plug". This alternate would essentially construct a Class V injection well, which requires prior approval from the NJDEP, which has not been granted in any such proposal to our knowledge.

As a result of exfiltration from the system, the geotechnical consultant and general contractor recommended that the areas of concern be excavated for exploration under their technical supervision, resulting in a hole some 15.2 m (50 feet) wide by 18 m (59 feet) long by 4 m (13 feet) deep (Figures 3 and 4).

Before the next phase of the remediation was initiated, two more sinkholes opened. A combination of graded rock backfill (with "geogrid reinforcing") and low mobility (compaction) grouting by a specialty contractor was attempted to complete the remediation of four areas of concern (Figure 2). A total of six grout holes were planned and ten were actually drilled. The total amount of grout placed was 17¹/₂ m³ (22³/₄ cubic yards), injected in 0.6-m (2-foot) grouting stages until the surface was reached. A specified "volume cutoff" of ³/₄ m³ (1 cubic yard) was reached in 16 of the 0.6 m (2-foot) stages in the ten grout holes drilled. Hence, there was no proof
that a total of 9.75 m (32 feet) in these ten holes were fully grouted. This work was completed in December of 2010.

The authors were contacted in the fall of 2011 when additional sinkholes started to form in the parking lot adjacent to the stormwater system area (Figures 5 and 6). After discussions with the client and reviewing the available data for the stormwater system (which included a report from college maintenance personnel that the subsurface stormwater system had <u>never</u> "detained" water, even subsequent to large precipitation events), a Request for Proposal was prepared and sent to three prospective bidders, including the grouting contractor that performed the original low-mobility remediation (who declined to bid).

The other two contractors contacted provided closely competitive proposals, but previous history and the



Figure 3. Exposed rock and sinkhole throat at bottom of stormwater system.



Figure 4. Reinstallation of stormwater system (note graded rock in sinkhole at bottom right of photo).

ability to mix on site were important in selecting the winning bidder, Compaction Grouting Services (CGS).

Grouting Concepts

In consideration of the potential problems extant at the site, it was deemed necessary to have a flexible investigation and remediation program (e.g., Fischer and Fischer, 1995). The bid specifications included provision



Figure 5. Parking lot sinkhole adjacent to stormwater system.



Figure 6. Parking lot sinkhole adjacent to stormwater system.

for both high- and low-mobility grouting operations using varying proportion of cement, water, fine (e.g., mason) sand and an anti-shrinkage/fluidizer agent (in this case bentonite). Grout was to be injected through vertical and angled exploratory probes (so as to reach areas below the system without compromising the existing system) that would be logged by experienced geotechnical personnel. Alternative drilling methods were invited in the specifications and costs provided by the bidders. For economy and expediency, the grout holes were advanced using air-percussion (hydro-track) equipment.

The remediation was to be performed by a firm experienced in karst grouting. Mixers and pumps had to be able to handle a range of expected grout blends and viscosities, including the provision for a setting agent, which could change from location to location and depth upon the judgment of the grouting technician in charge. Potential ground heave was closely monitored during the grouting operations.

The need to maintain effective infiltration, as well as the variety of conditions expected during drilling within and immediately adjacent to the system required a flexible drilling and grouting program. The lack of useful and reliable subsurface information increased the original concerns for performing a quality job. To exacerbate our geotechnical concerns, the first exploratory probe hole drilled encountered an 5.5-m (18-foot) open cavity in the parking area. That hole was less than 3 m (10 feet) from the system and was initially drilled to isolate the stormwater system for remediation.

Grouting Operations

The stabilization program began near the subsidence features by drilling and grouting about 3 m (10 feet) from the detention/infiltration system, working outward from the aforementioned system. These holes were either tremie grouted or grouted under low pressure (69-138 kPa or 10-20 pounds per square inch [psi]). The grouting began using high mobility grout produced and injected through tremie method using a ChemGrout® (CG 600 3X8DH, Figure 7) in an attempt to seal off small passages leading to the system. This system used a colloidal mixer, agitation tank and a high pressure piston pump. However, high grout takes were experienced, indicating that bedrock cavities/openings were more extensive than originally anticipated; so a lowto mid-mobility (low-mobility grouting methods using a thinner, 15- to 20-cm [6- to 8-inch] slump grout mix) grout was used except at select locations where drilling air losses were minimal and the grout holes were greater than 3 m (10 feet) from the system. The mid- to low-mobility grout was mixed and delivered by a 7.6 m³ (10 cubic yards) capacity mobile site mixer and a Putzmeister TK 15 HP grout/ cement pump (Figures 8 and 9).



Figure 7. ChemGrout® CG 600 3X8DH.



Figure 8. 10 cubic yard mobile site mixer with Putzmeister TK 15 HP pump at rear.



Figure 9. Installing casing into the grout hole.

The specifications indicated that 1.5 m (5 feet) of sound rock was to be penetrated prior to terminating drilling. Grout injection points were drilled to depths ranging from 5.5 to 19.2 m (18 to 63 feet) with an average drilled depth of 8.7 m (28.5 feet). Some difficulties were encountered installing the grout pipe to the bottom of the drilled hole due to ledges of rock and poor quality rock. Grout takes for the injection locations ranged from about 0.02 to 2 m³/m (1 to 100 cubic feet per linear foot) of hole injected with an average grout take of 2.13 m³/m (23 cubic feet/linear foot) injected.

The original intent of the exploratory/grouting program was to seal the causal "throats" of the new sinkholes adjacent to or at the edge of the stormwater system to isolate it from potential areas of concern. As the work progressed (in heavy rains), a lengthy crack appeared to open in the central portion of the previously repaired system and parking lot requiring a revision to the planned program.

One unexpected problem with the grouting operations did arise as a result of the unusual subsurface conditions. While mid-mobility grouting one hole some 6 m (20 feet) outside the system at the 9.75-m (32-foot) depth stage, grout did find its way into the chamber system at a compromised pipe joint. Pumping pressures (measured at the grout hole head) were just 138 kPa (20 psi) at the time. This necessitated the removal of the grout from the system by a bucket brigade manning 19-liter (5-gallon) pails and likely helped stabilize a small section of the system with connection to a bedrock cavity.

At the location of the aforementioned crack that appeared during initial grouting operations, the centerline between the two closest, linear chamber runs of the system was "marked out". An attempt was then made to penetrate the stone fill around the system using a skid-steer mounted air-track that uses drill casing with a bit that can be extracted through the installed casing. The idea was to grout below the stormwater system, using low-mobility methods, to the bottom of the system; then removing the remaining casing while pouring pea gravel into the casing to fill the void in the system's gravel. However, the air-losses within the stone fill prevented any cuttings from reaching the surface and that drilling effort was abandoned before the bottom of the basin was reached.

Site Subsurface Conditions

As should be expected in any grouting operation, particularly at a karst site, the authors' knowledge of the subsurface was refined as more data was derived from the drilling and grouting operations. The exploratory drilling operations and subsequent grout injections revealed at least one northwest/southeast trending solution feature, likely controlled by fracturing roughly perpendicular to the general geologic strike of the region. Another solution feature seemed to parallel one edge (long axis) of the system. Although no linear pattern of sinkhole formation was evident by reconnaissance, these features became evident through exploratory drilling by cavities at varying depths and a generally deeper bedrock surface, as well as significant grout takes.

The most problematic of these solution features trended through a corner of the system and into the area of the student center, in line with one of the borings performed prior to construction where concerns were noted during the data review. This feature was followed well outside the stormwater system in an effort to preclude further collapse in the parking lot and loading ramp areas.

One other aforementioned feature appeared to be below the system, parallel to its long axis. This feature was grouted using angle holes drilled from outside the system at about a 10 degree angle so as to penetrate below the basin without encountering it directly. A mid- to lowmobility grout was then placed only to the depth of the bottom of the system.

During the operations, two solution features indicated by drilling and grouting intersected near the northeasterly corner of the system where the largest grout takes were experienced. This area evidenced extensive grout hole connection, mostly through drilling air exiting another nearby hole. On one occasion, this cross-connection evidenced drilling air connection through two probe holes bypassing another almost directly in the middle. Grout hole connections indicated by grout movement was noted, but was far less prevalent than the drilling air connection.

Another feature appeared to be related to a stormwater inlet and pipe some 12.2 m (40 feet) from the system and 22.9 m (75 feet) from the closest area of concern. Minor subsidence was noted adjacent to the inlet. This area was grouted through two holes bracketing the basin using high-mobility grout as extensive cavities were not encountered. Some 3.4 m^3 (4½ cubic yards) was placed in one grout hole, which then appeared within the other.

Summary and Conclusions

New Jersey regulations and space concerns are making subsurface stormwater detention/infiltration systems (with some form of preliminary treatment) more common in non-karst regions. However, as with aboveground stormwater detention, karst concerns have been accepted by some Municipal and State regulatory groups as a sound reason to completely eliminate the infiltration portion of the system. Thus, impermeable liners and qualified inspection of the subgrade by karst-experienced personnel have been more commonly recommended at sites underlain by carbonate bedrock.

As a result of the sinkhole problems in the stormwater detention/infiltration system, the stormwater inlet/dry well basins installed during previous construction were being eliminated by sealing the bottoms with concrete.

The exploration and remediation work for this subsurface stormwater detention/infiltration system was a most challenging project. It required a combined effort by a number of groups and individuals that has apparently yielded a functioning system at a difficult karst site. College administrative and maintenance personnel provided information and assistance that greatly increased the efficiency and effectiveness of the drilling and grouting operations. The flexible exploratory grouting program directed by experienced geotechnical personnel was implemented through a competent and cooperative grouting contractor and experienced crew.

The various combinations of vertical and angled drilling seemed successful and the contractor's ability to vary the grout mix upon short notice was invaluable considering the highly variable conditions below the site. Additionally, the system appears to detain water after precipitation events as a result of the remediations described herein, yet still effectively allows infiltration.

As with most grouting projects, these operations were deemed complete without full knowledge of the extent of solutioning in the area of concern and the ability of any grouting concept to eliminate all future problems. However, to date, no evidence of additional problems have revealed themselves in the vicinity of the subsurface detention/infiltration basin.

More than 245 m (800 feet) away, however, a sinkhole appeared at a combination catch basin and dry well located in an older portion of the campus underlain by the Allentown Dolomite. As important infrastructure was not threatened, a simple fix was employed; excavate in an effort to find the throat, inspection, flooding and the introduction of a "pumpable flowable fill" mix.

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NEED FOR A STANDARDIZED APPROACH TO CHARACTERIZING, PERMITTING, AND CONSTRUCTING LANDFILLS IN KARST GEOLOGIC SETTINGS

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Abstract

The challenges presented by geohazards play a significant role in the permitting of environmental facilities, particularly those situated in karst geologic settings. With regards to landfills, and specifically to municipal solid waste (MSW) landfills, regulators have a significant responsibility to protect the environment and must make decisions regarding the siting and permitting of these facilities. While these decisions are based on their objective assessment of site-specific characterization information, their decisions are often scrutinized by the public and by the owner/permittee...entities that often (and usually) have contrasting interpretations of the same site characterization information. The Florida Department of Environmental Protection (FDEP) has initiated an innovative approach to help the agency in the decision-making process by convening a Technical Advisory Group (TAG), comprised of several agencyand industry-recognized experts who are experienced in the investigation, characterization, permitting, and construction of engineered facilities in karst settings. Through a process involving the compilation and assessment of various site-specific factors, the TAG is working with FDEP personnel to develop specific and objective guidelines that can be used by owners, permitees, consultants, and the agency in developing investigation, characterization, design, construction, operations, and monitoring strategies for facilities overlying karst geologic conditions. The activities of FDEP and its TAG are actively reviewed by the public, who have also been requested by FDEP to participate in the process of developing these guidelines. The objectives for making this presentation are twofold, specifically to provide information to and then solicit information from the conference participants (and readers). The approach being taken by FDEP and the TAG focuses on technical

issues regarding the investigation, characterization, design, and construction of engineered facilities in karst geologic settings. The authors recognize that these technical issues impact all engineered facilities, not just those constructed for environmental applications. Therefore, the approach developed by FDEP may benefit other agencies, owners, and consultants who face similar challenges. The participants at this conference likely have specific experiences and can offer recommendations that will ultimately be beneficial to the DEP and the TAG. In this presentation, the authors will actively engage the participants and will request input based of their experience and expertise.

Introduction

It is often said that we can only be certain of two things... death and taxes. Geotechnical and geoenvironmental professionals can safely add three more relative certainties: (i) as a society we continue to generate large amounts of garbage (i.e., MSW) that require safe long-term disposal; (ii) few people want MSW disposal facilities (i.e., landfills) located "in their backyard"; and (iii) geohazards that restrict the location of these unwanted landfills come in all sizes and shapes and exist across the U.S. Regarding modern landfills, which have a nearly 20-year duration track record of demonstrated performance, there is a reticence of the populace to view this as a "societal need" and prefer that the problem be shifted to others at other locations. Regarding geohazards that pose problems to landfills, karst represents one of the most significant geologic hazards in the State of Florida, which is one of the most populated states in the country. Across Florida, and particularly in Central Florida where the karst is prevalent and the population is dense, it is easy to project a major problem when a societal need runs headlong into geologic constraints.

In anticipation of the collision course, the Florida Department of Environmental Protection (FDEP) has taken a proactive course of action to develop technically rigorous recommendations regarding the siting, permitting, design, construction, operations, and monitoring of MSW facilities in the State that need to be located over karst terrain. This paper will identify the State-specific problems that face the geologic, geotechnical, water resources, and geoenvironmental professionals who must deal with the often competing demands placed by society in dealing with the disposal of MSW and the locations of the disposal facilities. The authors will then describe a unique State-initiated proactive strategy for addressing the waste disposal problems caused by the challenging geologic conditions, with an objective of developing technically defensible and objective regulations for MSW disposal facilities in Florida. Finally, the authors will solicit opinions and experiences from the participants of the conference regarding improvements to this initiative, recognizing that "do nothing" or "take the waste elsewhere" is not a sustainable alternative.

The Problem...MSW and Geology

Before a strategy can be developed, a sense for the magnitude of the problem needs to be recognized. In Florida (as well as in many parts of the country), the "problem" is a combination of the need for landfill airspace and the prevalence of karst in the underlying geologic formations. A brief summary of these problems follows.

MSW in Florida – Past and Future Trends

Regarding solid waste practices and experiences, Florida follows many of the trends evident across the country. Figure 1 shows the reality of solid waste generation in Florida over the past 20 years. The downward trend since 2005 is a combination of country- and State-wide emphasis on waste reduction and on the recent economic conditions in the U.S. If these trends are compared to national trends and coupled with the population, results indicate that in Florida, the waste generation can be represented as approximately 3.5 kg (7.8 pounds) per person per day compared to a national average of 2.0 kg (4.4 pounds) per person per day. Consistent with national trends, prosperity leads to an increase in MSW generation per person. When these trends are coupled with the future estimated population growth in Florida (Figure 2), the impact of population growth on solid waste disposal needs is staggering. Interestingly, the Florida population growth trend of about 250,000 people per year (ppy) is approximately 10% of the projected national population growth trend of 2,500,000 ppy (FAIR, 2006). Clearly, the popularity of the 4th most populated state in the country is projected to increase over the next several generations. As can be seen in Figure 1, it would require an extreme paradigm shift in public policy, public response, and waste disposal practices to have a significant impact on long-term MSW disposal needs.

To further demonstrate the MSW disposal issues facing Florida, consider the locations in Florida where people want to settle. Figure 3 shows the current population density across the State. People clearly like to live in Central Florida.

Finally, over the past several years, most states have seen an overall reduction in the number of solid waste disposal facilities. This is demonstrated in Figure 4, which reports the number of active MSW disposal facilities across the country. The national trend over the past 20 years clearly shows that the number of facilities







Figure 2. Florida Population Projections (FL EDR, 2011).



Figure 3. Florida Population Density (FL EDR, 2011).

has precipitously decreased to only (on average) 39 MSW disposal facilities per state. Currently Florida has 40 active landfills and 80 closed facilities. The question is "Where do Floridians place waste in the future and how much capacity is needed?"

Karst Geohazards in Florida

Karst and the underlying problems associated with the geologic conditions are well known to most Floridians, especially to our conference co-organizers from the University Of South Florida in Tampa. Perhaps the most famous (infamous) is the May 1981 "Winter Park Sinkhole" measuring approximately 98-m (320-ft) in diameter and 27-m (90-ft) deep that comprised almost an entire city block. Although detailed formal historical records may be infrequent, the Florida Geologic Survey (FGS) has recently compiled and published records, primarily to assess the impacts of subsidence and sinkholes on groundwater resources. Figure 5 shows the six districts of Florida identified by the FGS and present locations of reported subsidence.



Figure 4. MSW Landfills in the U.S. (USEPA, 2009).

As shown on this figure, the two districts comprising Central Florida (i.e., Southwest District and Central District) account for 85 percent of the nearly 2,300 reported episodes of subsidence. When the Northeast District is added to this list, the locations of nearly 95 percent of the reported episodes are included. Independent records maintained by Florida's Water Management Districts (WMDs) and verbally provided to the authors provide nearly identical results. Clearly, the problems of subsidence and sinkholes are regionalized. The FGS used data compiled from around the State to develop Florida Aquifer Vulnerability Assessment (FAVA) maps. The FAVA for the prolific Florida Aquifer is presented in Figure 6.



Figure 5. Map Showing Reported Subsidence Areas (FDEP, 2010, written communication).



Figure 6. Florida Aquifer Vulnerability Assessment (FAVA) Map for the Floridan Aquifer (FDEP, 2010, written communication).

This map was developed when FGS considered: (i) depth to the groundwater table; (ii) hydraulic head difference in the aquifer; (iii) thickness of the confining unit; (iv) distance to known karst features; (v) overburden soil permeability; and (vi) aquifer system overburden. Comparing Figures 5 and 6 provides the compelling observation that the most valuable groundwater resource in the State is most vulnerable in the areas where virtually 95 percent of the reported subsidence is located.

Finally when one links these findings regarding geologic and hydrogeologic conditions with the previous section regarding solid waste needs, a foreboding observation develops. It is anticipated that the areas where the population density is the highest (Figure 3) are where there will be the largest need for landfill disposal airspace in the future. Further, this area is where the potential for subsidence and sinkholes is highest (Figure 5) and where the Floridan Aquifer is most vulnerable (Figure 6). Furthermore, it is noted that the areas of subsidence and aquifer vulnerability, hereinafter referenced as "sensitive" areas, comprise nearly 60 percent of the total land area in the State. Clearly, a hasty reaction to simply prohibit the siting of landfills in these sensitive areas would place a hardship on other areas of the State where the landfills (likely large landfills) would be sited and would result in significant adverse financial impacts to residence of Central Florida due to high transportation costs. FDEP anticipates that future MSW landfills will be sited within Central Florida. These figures indicate that there are significant technical and environmental challenges across the State. Technical differences of opinions are inevitable between environmental groups, landfill developers, the public, and the FDEP unless consistent, defensible, and fair solid waste policies and guidelines are developed and enforced.

The Solution...Development of FDEP Guidance Documents

The FDEP has developed and currently maintains and enforces solid waste regulations in the State that exceed the U.S. Environmental Protection Agency (USEPA) "Subtitle D" requirements regarding the siting, design, construction, operations, and performance of MSW disposal facilities. The FDEP has followed USEPA guidelines and like other states that experience karst geologic conditions (including Alabama, Arkansas, Kentucky, Minnesota, Pennsylvania, and Tennessee), has taken aggressive regulatory positions regarding the need for the MSW permit applicant to provide long-term protection of groundwater resources by establishing: (i) landfill design guidelines; and (ii) groundwater monitoring guidelines. With regards to groundwater monitoring requirements, these State regulations acknowledge that the groundwater regime in karst geologic settings is significantly governed by discrete conduit flow, in contrast to continuous porous media flow in aquifers comprised of granular media. The FDEP has taken a strong position that its policies are directed to protecting groundwater and minimizing potential adverse risks to its aquifer systems. Therefore, the FDEP regulations explicitly recognize the importance for the applicant to demonstrate an understanding of the groundwater flow regime and develop a groundwater monitoring system for the site-specific conditions. These regulations apply to sites located in karst and non-karst settings.

FDEP Rules and Regulations

In addition to its influence on the groundwater flow regime, karst can also impact the structural <u>stability</u> of the landfill itself. The FDEP regulations (as well as the regulations in most other states) address issues of structural stability. Specifically, several specific sections of the Florida Administrative Code (FAC) are cited to provide examples of how regulations (and regulators) address issues related to landfill stability (italics added by authors for emphasis):

- Rule 62-701.300(2)(a) regarding *prohibition for siting requirements* for all solid waste disposal facilities states... "unless authorized by a Department permit or site certification in effect on May 27, 2001, or unless specifically authorized by another Department rule or a Department license or site certification based upon site-specific geological, design, or operational features, no person shall store or dispose of solid waste.... in an area where geological formations or other subsurface features will not provide support for the solid waste;"
- Rule 62-701.340(3)(a) regarding the *location requirements* for all landfills states that ..."the site shall provide structural support for the facility including total wastes to be disposed of and structures to be built on the site;"
- Rule 62-701.400(3)(a)2 regarding the *design requirements* for all landfills states that composite soil and geosynthetic liners shall be ..."installed upon a base and in a geologic setting capable

of providing structural support to prevent overstressing of the liner due to settlements and applied stresses;" and

• Rule 62-701.410(2)(b) regarding *geotechnical site investigation requirements* for all landfills and construction and demolition (C&D) debris disposal facilities states the ..."prior to any construction on the landfill site, the engineer shall define the engineering properties of the site that are necessary for the design, construction, and support of the landfill and all installations of the facility and shall...explore and address the presence of muck, previously filled areas, soft ground, lineaments, and sinkholes."

These regulations leave significant latitude for the applicant to make the requisite demonstrations and there are opportunities for subjective judgment. For example, with regards to geotechnical site investigation requirements above, one engineer may believe that the site can be adequately characterized using 1 boring per hectare (2.4 borings per acre), while another may believe that variability at the site warrants a density of greater than 4 borings per hectare (10 borings per acre). In many cases, the regulations leave decisions to the discretion of the professionals tasked with preparing the permit application. The FDEP, however, recognizes that even comprehensive site-specific geotechnical investigation and geologic characterization studies require the educated judgment and opinions of professionals regarding an interpretation of data and facts. This interpretation of these study results must be provided in an application prepared on behalf of the applicant that demonstrates compliance with the FDEP regulations. To issue an FDEP permit for an MSW facility, the applicant must provide "reasonable assurance" to the FEDP that the proposed project will comply with the State regulations. Rule 62-701.200(94) importantly states that ... "reasonable assurance" means the existence of a substantial likelihood, although not an absolute guarantee, that the proposed activity and applicant will comply with agency rules, laws, orders and permit conditions. It does not mean proof that a facility will not fail." It is noted that this section of the regulations recognizes that the permitting test is for "reasonable assurance" not for "absolute assurance."

The landfill permitting process in Florida (and all other states) requires that professional engineers and geologists prepare technical applications that provide the previously stated "reasonable assurance." The permitting applications are first reviewed by the FDEP for regulatory compliance and are subject to the permit test for reasonable assurance. The permit application and the FDEP comments are then subject to public review and scrutiny. In many cases the interpretations of the geotechnical investigation and geologic characterization studies, as well as the FDEP opinions, are subject to an independent assessment by the public reviewers regarding regulatory compliance and reasonable assurance. In addition, particularly for permits involving controversial sites, the findings and interpretations of the public's review (often by other qualified professionals) will differ from those of the FDEP and the applicant's professionals. This often leaves the FDEP in the middle of technical disagreement between qualified professionals and the reality that regardless of its decision as a "referee", the FDEP will be the subject of rebuke and potential litigation from either the applicant or the public. The FDEP has successfully faced the realities of this "regulatory environment" since the promulgation of the USEPA's Subtitle D regulations. For sites and topics where controversy or technical challenges are anticipated, FDEP (and regulators in other states) have taken the initiative to develop "Technical Guidelines" to assist the applicant's understanding of the State's expectations regarding the permitting process.

For reasons described previously, there is significant applicant and public "response" regarding recent MSW landfill permit applications for sites in Central Florida. In addition, FDEP recognizes future challenges facing this region as summarized in the previous section of this paper. To address these issues, the next section describes a proactive approach that FDEP has taken regarding the siting, permitting, design, construction, operation, and monitoring of MSW disposal facilities located in karst geologic settings.

Development of a Technical Advisory Group (TAG)

To assist the agency in this initiative, the FDEP has commissioned a Technical Advisory Group (TAG) comprised of a number of engineers, geologists, and scientists from both the public and private sectors with expertise in karst assessment to help the agency in the development of additional technical guidance. This guidance will assist: (i) the applicant in its preparation of MSW permit applications; (ii) the FDEP personnel responsible for technical review of the permit application to verify compliance and reasonable assurance; and (iii) the public in its review and critique of the permit applications. The charge to the TAG is to assist the FDEP in the development of technical guidance for the siting, permitting, design, construction, operation, and monitoring of MSW disposal facilities sited in karst settings. The two primary objectives of this technical guidance includes specific recommendations that will help: (i) the FDEP decide how to evaluate these permit applications and then issue the solid waste disposal permits; and (ii) the applicant know what information should be submitted in these permit applications. Importantly, the FDEP required that siteand region-specific recommendations be provided but acknowledged that in developing the guidance, there needs to be a balance between "cost of assessment and investigation" and the "risk of failure." Furthermore, the guidance needs to apply both "good science" and "reasonable judgment" when making recommendations. Finally, because the TAG members represent a diverse group of professionals, FDEP required that members set aside personal interests, if any exist, and focus on what is really "good" for Florida.

Specific Objectives of the TAG

Recall that the primary objective of the USEPA and FDEP regulations was protection of groundwater resources. FDEP recognized the USEPA findings that essentially validated the intention of the Subtitle D regulations. Specifically, the findings presented in Bonaparte, et al, (2002) demonstrated that the composite liner system design and the leachate management system design and operations requirements promulgated by the Subtitle D regulations resulted in landfill liner systems that were protective of groundwater. As mentioned previously, the challenge in the geologic setting in Central Florida is to assure the structural integrity of the liner system. Therefore, the FDEP charge to the TAG was to provide specific guidance to help the FDEP gain "reasonable assurance" that the foundation below the landfill would provide sufficient strength to maintain the structural integrity of the landfill liner system. To accomplish this objective, the FDEP requested that the TAG develop specific guidance regarding (in order of priority): (i) using physical and geophysical techniques for characterizing sinkhole potential of a site; (ii) determining if potential sinkhole risks for a site are low, moderate, or high; (iii) deciding when a site cannot be used or can be used if properly stabilized; (iv) stabilizing a site and determining that stabilization was achieved; and (v) monitoring a disposal facility for sinkhole formation. A brief discussion of the approach used to address each of these tasks and preliminary recommendations by the TAG follow.

Characterizing Site for Sinkhole Potential

The first and most important step is to adequately characterize the potential site. At a minimum, this task includes: (i) review of geologic information regarding the area, particularly the conditions within a 16-km (10mile) radius of the site; (ii) review of historical aerial photographs of the area within a 16-km (10-mile) radius spanning several years (or decades when possible) followed by physical inspection of the site with photos "in hand"; (ii) geophysical investigation along several transects, including orthogonal transects that intersect at the location of specific invasive subsurface borings/ soundings; and (iv) physical invasive investigation, sampling, and in situ testing. This strategy recognizes that the potential for sinkhole development starts at a region-wide level before it eventually gets to a sitespecific consideration. If there are reported subsidence features within the 16-km (10-mile) radius, reports should be cited and details of the features should be included in the permit application. With regards to the geophysical testing, electrical resistivity and ground penetrating radar (GPR) seem to be common techniques that have been used successfully in Florida. Other techniques will be considered. It is critically important that these non-invasive tests be "calibrated" at specific locations by having the transects intersect select boring/ sounding locations. Invasive testing can include hollow stem auger or mud rotary drilling, with the latter being preferred due to the ability to note "rod drop" and "slurry loss." Soil samples and rock cores should be collected. In situ testing can include the Standard Penetration Test (SPT) or the Cone Penetrometer Test (CPT). The TAG is currently considering the recommended minimum number of geophysical transects, the depth and extent of coring, and the minimum number of borings/soundings, as well as the recommended laboratory tests. The recommendations will vary depending on the findings from the geological and aerial photograph review.

Assessing Sinkhole Potential Risks

Perhaps the most difficult task facing the TAG is the assessment of the risk of a sinkhole developing at the proposed MSW disposal site. The FDEP would like

the assessment to report a "high", "medium," or "low" risk to the landfill stability in the event of sinkhole activation. Essentially this implies pre-formation information regarding the potential size of the sinkhole, as large sinkholes present significant challenges to the landfill liner integrity. The TAG is considering a detailed assessment of the FGS and WMD files regarding the location and size of the reported subsidence features so that regional lessons can be reported based on past performance. At a minimum, the TAG hopes to adopt or develop objective criteria that defines high, medium, and low risk.

Evaluating Site Suitability

One of the objectives from the previous task (i.e., assessing risk should a sinkhole develop) is to develop objective evaluation criteria to assess site suitability for a MSW disposal facility. Although in its preliminary state, the TAG anticipates that there will be a strong correlation between the high, medium, and low classification in the previous step and the assessment of site suitability. The TAG recognizes the argument from applicants that "all sites are potentially suitable for development provided there is sufficient stabilization and adequate engineering control." The FDEP does not necessarily want to "condemn" a site a priori, but clearly wants to make the applicant aware that certain geologic conditions will render a site essentially "unsuitable "due to the likelihood of sinkhole development and the risk of the sinkhole on the integrity of the landfill liner system. Figure 7 provides an example of a potentially "unsuitable" site. This aerial map, when combined with historical photos from the previous 20 years, showed a gradual and steady development of large sinkholes that extend to the ground surface and "grow" over time. For most sites (and in particular this site), it is important to understand the geologic setting and the sinkhole-forming mechanism to assess whether it is economical to "arrest" future sinkhole development or better to simply abandon the site.

Defining Site Stabilization Measures

One of the major contributions of the TAG will be to help the FDEP define minimal stabilization efforts that may be required to improve the suitability of the site to a level that provides "reasonable assurance" to the FDEP that the site can be developed in compliance with the FDEP regulations. Depending on specific site conditions, techniques may include (but are not



Figure 7. Example of a Potentially Unsuitable Site.

limited to) deep dynamic densification, local or largescale grouting, reinforcement, and over-excavation and replacement. The stabilization efforts will require that the applicant demonstrate the effectiveness of the selected stabilization remedy. With reference to Figure 7, it is difficult to envision any strategy that does not completely over-excavate and replace all of the soil overburden soil followed by treatment of the foundation bedrock. One aspect of stabilization that concerns the TAG is what is referenced as "The Dutch Boy Solution," in which the plugging of one hole in the dike simply caused a new hole to form. Stabilization alternatives will need to consider "site wide" stabilization efforts or at least the impacts of "localized" stabilization efforts on overall site stability.

Monitoring for Sinkhole Formation

The FDEP acknowledges that the construction of a landfill, particularly large facilities, can alter the predevelopment groundwater flow regime. The landfill has a beneficial effect of loading the foundation soils and restricting the vertical infiltration of water. However, site development plans can have adverse effects. Specifically, the design of surface water management ponds, localized infiltration of surface water, and excavation (i.e., unloading) the foundation soils can increase the potential for sinkhole development. The TAG anticipates that there will be recommendations for monitoring the site, as well as the surrounding parcels of land, for early indications of new sinkhole formation. Unfortunately, simple settlement monitoring is insufficient because the solid waste itself decomposes over time resulting in significant mass loss and self-weight compression. These recommendations will include provisions by the applicant for modifying operations and addressing these features should they occur.

This section identified the overall strategy being undertaken by the TAG to assist the FDEP. The primary objective of the TAG is to provide <u>objective</u> recommendations and <u>minimum</u> expectations regarding exploration and investigation programs that are based on regional- and site-specific conditions. The goal is that these efforts and objective recommendations will provide a "level playing field" for all MSW permit applicants.

The Solicitation...Obtaining Feedback and Recommendations from Karst Experts

The purpose of this paper was to describe a strategy currently being implemented by the FDEP to improve the MSW landfill permitting process in karst geologic settings. Several of the charges to the TAG involve attempting to quantify a complex geologic phenomenon. The authors recognize that the participants at this conference (and readers of the proceedings) may have specific experience that could benefit the FDEP and its TAG. Therefore, the authors explicitly solicit feedback and suggestions regarding the strategy identified. Specifically, are the participants/readers aware of or have recommendations regarding: (i) other similar efforts by other agencies that would benefit the TAG, (ii) specific experience regarding the karst systems in Florida that need to be considered; (iii) geophysical testing techniques or test frequencies/densities that should be considered; (iv) stabilization options that have (or have not) worked effectively; and (v) specific experience regarding the characterization and monitoring of MSW landfills that should be considered. The authors recognize that the experience may be region-, formation-, and/or site-specific, but the experience of the participants will be useful in helping complete the TAG's mission.

Conclusion

The FDEP has developed and currently maintains and enforces solid waste regulations in the State that exceed the national standards but desires to improve the MSW landfill permitting process. The State of Florida is currently the 4th most populated State and Floridians generate solid waste at a rate that exceeds the national average. MSW landfills are a necessary component of Florida's future anticipated growth. Unfortunately, Central and Northeast Florida comprise nearly 60 percent of the total land area in the State and is founded on geologic formations that have experienced significant subsidence due to sinkholes. These same areas are within zones where the valuable groundwater resources are considered most vulnerable and include areas of the highest population density. The FDEP has developed a strategy for providing MSW landfill permit applicant with objective recommendations for investigating future potential landfill disposal sites. It is the hope of the FDEP and its TAG that these recommendations will help the permit applicants provide the FDEP a "reasonable assurance" that the siting, design, construction, operations, and monitoring of the proposed facility is in compliance with FDEP regulations. The authors solicit feedback from conference participants (and proceedings readers) regarding techniques to improve the strategies identified in this paper.

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A CALIBRATION TEST OF KARST COLLAPSE MONITORING DEVICE BY OPTICAL TIME DOMAIN REFLECTOMETRY(BOTDR) TECHNIQUE

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Abstract

Brillouin Optical Time Domain Reflectometry (BOTDR) is a distributed fiber optic strain sensing systems based on Brillouin scattering. This technique may potentially become a useful tool to monitor and predict karst collapse, especially for linear infrastructure such as roads, highways, and railways. This paper introduces a calibration device which is used to establish the relationship between fiber deformation and underlain soil -cave dimension. Based on the deformation characteristics of the sinkhole collapse, the mechanical relation between soil body and sensing fiber is analyzed, and a simplified model of collapse is proposed for testing design. The experimental tests are carried out through the designed equipment to investigate the effect of the sinkhole's size and the overburden stratum's thickness on embedded optical fibers. Firstly, the sinkhole formation process was stimulated with the orderly changes in load on the optical fiber. Secondly, the impact of the changes of sinkhole size on the sensing fiber monitoring was analyzed. It shows from the experiment results that the strain change in the sinkhole formation process can be monitored by distributed optical fiber sensing technology and the sinkhole size can be reflected through the optical fiber strain range. Besides, the sensibility of coated optical fiber in sinkhole collapse monitoring tests varies between different types of optical fibers. Due to the effective response of the distributed optical fiber sensing technology to sinkhole forming and evolving, it can be adopted in the monitoring for potential sinkhole collapse.

Preface

Karst is widely distributed in Southwest China . Along with the large-scale development and rapidly increasing of human activities, geological disasters related to karst have become prominent, especially karst collapse (sinkhole collapse), which has become the major geological problems of highways, high-speed railways, oil & gas pipelines and other projects in karst region (Chen, no date). How to avoid karst collapse, specially its potential threat to existing projects, has become a significant challenge for engineering geologists.

The most effective means to avoid geological disasters is prevention. Therefore, monitoring and early warning of karst collapse are particularly important. Current monitoring methods for karst collapse includes Ground Penetrating Radar (GPR) survey, Time Domain Reflectometry (TDR) technique and monitoring of the water or air pressure changes in underground karst system. Periodical GPR survey may find potential collapse abnormalities, but due to its strict working environment, limited detection depth, professional operation and high cost, it has limitations for long-term monitoring. TDR technique has many advantages, such as mature technology, distributed monitoring, antiinterference and comparatively low price. However, TDR cannot be used to monitor the formation process of karst collapse because it receives only the signal from the monitoring object which is effected by shearing force, tension or both combined. Monitoring water and air pressure changes in underground karst system can only forecast the collapse risk of the karst fracture around the monitoring points. But it cannot point out the specific location where karst collapse may occur. Therefore, traditional monitoring methods cannot meet the demand for sinkhole collapses monitoring or forecast, which usually occurs abruptly and indefinitely. Brillouin Optical Time Domain Reflectometry (BOTDR) is a distributed fiber optic strain sensing system, which can detect temporal and spatial changes of external physical parameters at large-scales and on a continuous basis (Tang et al., 2006). Nevertheless, there are still many problems in the application (Jiang et al., 2006; Li et al., 2005; Meng et al., 2011). According to the deformation characteristics obtained from sinkhole collapse modeling and calibration testing, we analyzed the mechanic relation between the soil and sensing fiber, and studied the application of distributed optical fiber sensing technology as a predictor of potential sinkhole collapse.

Monitoring principle of optical fiber sensing technology

The distributed optical fiber sensing technology is based on three spectroscopic analysis methods including Rayleigh scattering, Brillouin scattering and Raman scattering. Rayleigh scattering is an elastic scattering which does not cause frequency drift in the optical fiber. Brillouin and Raman scattering are nonelastic scattering which may cause frequency drift in the optical fiber (Yu, 2006). Brillouin scattering arises from the interaction between optical and acoustic waves propagating in the optical fiber (Figure 1). The relationship between Brillouin scattering frequency and the temperature or strain of the optical fiber is linear. So, the changes in temperature or axial strain can be calculated according to the amount of the frequency drift in the optical fiber. In order to obtain the drift of the axial strain only, one optical fiber sensor without external force or a temperature sensor is adopted to offset the drift by temperature change.

The relationship between the center frequency drift and axial strain in optical fiber

$$\mathbf{V}_{\mathbf{B}}(\boldsymbol{\varepsilon}) = \mathbf{V}_{\mathbf{B}}(\mathbf{0}) + \frac{\partial \mathbf{V}_{\mathbf{B}}(\boldsymbol{\varepsilon})}{\partial \boldsymbol{\varepsilon}} \boldsymbol{\varepsilon} \quad (1)$$

where:

 $VB(\varepsilon)$ - Brillouin scattering frequency of axial stretched optical fiber;



Figure 1. The principle of BOTDR.

VB(0)- Brillouin scattering center frequency of no stress optical fiber;

 $\partial V_B(\varepsilon)/\partial \varepsilon$ -strain coefficient;

ε- optical fiber axial strain.

The strain coefficient usually is 0.5GHz/%, which is decided by the material properties of the optical fiber. The optical fiber strain is about 0.0493MHz/µ ϵ (Liu et al., 2006) when the incident pulse wavelength is 1.55µm. The center frequency drift is influenced by the temperature changes. The experimental temperature variation is less than 5°C, so the temperature effects were not considered.

BOTDR is a distributed fiber optical strain sensing technology based on Time Domain Reflectometer (OTDR) technique. According to the OTDR principle, the scattering position can be determined by measuring the scattered laser echo time. The distance between the pulse laser injection point and any point in the optical fiber can be counted by the following equation.

$$Z=cT/(2n)$$
 (2)

where:

Z-distance;

c- light velocity in vacuum;

n- refractive index of optical fiber;

T-time difference between sending and receiving a pulse laser.

According to Equation (1), the axial strain distribution of the optical fiber can be calculated (Zhang et al., 2003; Shi et al., 2005). According to Equation (2), the position where strain occurred can be calculated.

The karst collapse monitoring model

The working principle of BOTDR for collapse monitoring is based on the development of a karst soil void that manifests as deformation of the overburden time until a cover-collapse sinkhole forms at the surface. So, a sensing fiber can be buried where collapse may probably occur and the fiber deforms under the load coming from overlying stratum due to the development of a soil void. The location, scale and development of soil void can be well understood based on the analysis of temporal and spatial variation of sensing fiber strain.

Deformation compatibility of fiber and soil

The formation of soil void is the result of varied superimposing collapse factors, which causes overlying soil deformation or potential collapse. The key to the BOTDR monitoring is the accurate finding of such deformation. Reasonable distribution of the sensing fiber to keep synchronal deformation with the soil mass is important during soil void monitoring. The placement of the sensing fiber is determined by the distribution features of karst collapse in the monitoring region. In our research, the model was simplified so that the sensing fiber goes through the center of the soil void overburden stratum. During the development of collapse, deformation of the soil mass occurs gradually, and also the fiber buried there is stretched downward with sliding deformation called compatible deformation.

Compatible deformation of fiber and soil is not only related to the fiber material and its structure, but also is influenced by the interaction between soil and fiber. And this interaction will be explained by mechanical analysis in the following discuss.

Referring to mechanical relationship between fiber and soil as Figure 2 shows, the fiber internal force variation (dT) can be demonstrated as below:

$$dT = (\pi D) \tau dx = (1/4 \pi D^2)$$
. E. de (3)

where:

E-elastic modulus of fiber;

T-shear stress on the fiber surface;

D- diameter of the fiber;

dɛ-gradient of strain variation;

dx-differential length along fiber axial direction

Thus (Li et al.):

$$\tau = \frac{DE}{4} \frac{d\epsilon}{dx} \tag{4}$$

Shear stress exiting on fiber surface is produced by the friction between soil and fiber cover. Sliding friction is smaller than maximum static friction, so sliding friction is taken in the analysis.

$$\tau = -f = -\mu \text{ N} = -\mu G \pm = -\mu \gamma h \qquad (5)$$

where:

f- friction between soil and fiber cover;

 μ - coefficient of friction;

N- vertical pressure imposed on fiber by overburden soil;

 $G\pm$ -weight of incumbent soil;

- γ equivalent bulk density of incumbent soil;
- h thickness of incumbent soil.

According to Equations (4) and (5):

 $\mathbf{d}\boldsymbol{\varepsilon} = -\frac{4\mu\gamma\mathbf{h}}{\mathbf{D}\mathbf{E}}\,\mathbf{d}\mathbf{x} \tag{6}$



Figure 2. The mechanic relationship between soil and optical fiber.

As explained in the theory mentioned above, when relative displacement occurs between fiber and soil under the condition of invariable fiber material, constant soil thickness and bulk density, stress is directly proportional to the coefficient of friction. Force transmission of sensing fiber buried in the soil mass relies on the friction between fiber cover and soil. Thus, fiber deformation happens while soil is deformed.

Simplification of collapse monitoring model

As soil void develops, incumbent soil load and void scale are critical to the magnitude and distribution of the stress around the developing void. According to the key monitoring factors and the deformation compatibility between fiber and soil, collapse mechanic model was simplified and collapse simulation experiment system was designed.

During the formation of soil voids, the friction imposed on optical fiber at the edge of void and its influence area are changeable. Thus, optical fiber fixation should be considered in the model design (Liu et al., 2010; Yao et al., 2005). Intertwist, one of the fixation methods, is adopted which can express the way how friction varies with loads effectively (Figure 3).



Figure 3. Simplified sinkhole model.

Experiment system

The displacement of optical fiber relative to soil varies with the load. This can be simulated by an experiment system which consists of a clamping wheel, adjustable supporter, dial indicator and vertical loading system. And the formation of soil voids with 0.5~2.5m span under different loads can be simulated as well.

Test and analysis

Two types of experiments, variable load in certain distance and variable distance under certain load adopting ordination and GFRP optical fiber, were carried out, respectively.

AQ8603 Optical Fiber Strain Analyzer(BOTDR) produced by the ANDO corporation of Japan was used to measure the strain distribution in the optical fiber. The main index of the instrument is shown in Table 1.

Test under stepwise variable load in certain distance

The experiment simulates the load changes of the soil cave roof by loading and unloading on the optical fiber to analyze the changes of the axial strain and the optical fiber deformation.

Experiment process

Experiments were performed for Glassfiber Reinforced Plastic (GFRP) optical fiber and ordinary optical fiber respectively. The positions were recorded by the labels on it. For GFRP optical fiber, fixed segments were 920-923m and 924.5-927.5m, and the loading point at 923.5m. For ordinary optical fiber, fixed segments by winding is 1065-1068m and 1069.5-1072.5m, and the loading point at 1068.75m. The loading point deformation and strain in the sensing fiber were measured by dial indicator and AQ8603. The loading step follows 0kg, 0.5kg, 1kg, 2kg, 3kg and 5kg. Test data were recorded for every step loading and unloading.

Test data processing and analysis

According to its principle, the strain measured by the strain instrument is the integrated strain within 1m starting from the monitoring point (Wu et al., 2005; Yue et al., 2007). Taking the value got from connectivity test as the initial value of optical fiber, strain change is the difference between the loading test value and the initial value.

According to the strain change distribution as shown in Figures 4 and 5, under the same load the strain influence zoon of the GFRP optical fiber is smaller than that of the ordinary optical fiber. With increasing loading, the strain influence zoon (distance) becomes more significant for GFRP fiber. Due to the small friction coefficient between GFRP fiber and wound case, the friction length must be increased to obtain the enough friction . The strain change of ordinary fiber is larger than that for the GFRP fiber under the same loading conditions, which indicates that the ordinary optical fiber is more sensitive to load comparing with the GFRP fiber. In other words, the ordinary optical fiber can serve low loading very well. It

Technical Index		Optional parameter				
Measure distance		1, 2, 5, 10, 20, 40, 80km				
Pulse width		10ns	20ns	50ns	100ns	200ns
Dynamic range	±0.004%(2s)	2dB	6dB	10dB	13dB	15dB
	±0.003%(2s)	-	-	8dB	11dB	13dB
Length resolution		1m	2m	5m 11m 22m		
Strain test accuracy		±0.004%(2s)		±0.003%(2s)		
		(±0.01%)		(±0.005%)		
Strain test repeatability		<0.04%		<0.02%		

Table 1. AQ8603(BOTDR)Technical Index.

In the experiment, $\pm 0.004\%$ (2s) strain, 10cm sampling distance and 1m length resolution were adopted. Fiber connectivity was tested before the experiment.



Figure 4. The loading point strain change (GFRP).



Figure 5. The loading point strain change (Ordinary optical fiber).

is suitable to be used for the soil bearing low pressure or having a low cohesion with the fiber.

When the stratum which the optical fiber is buried in lost cohesiveness, the sensing optical fiber was gradually unloaded. Following the soil void overburden collapse, the optical fiber was finally separated from surrounding soil mass this process can be simulated by unloading experiment (Figures 6 and 7). Unloading experiment demonstrates that the sensing optical fiber can respond to the deformation of sinkhole collapse, and the position of the coverboard loading and the optical fiber axial strain has good relationship. The overburden stratum thickness of an incipient sinkhole, the friction between the soil and optical fiber, and the cohesion of soil mass must be considered when choosing optical fiber. Therefore, the correct optical fiber must be selected in order to avoid the elastic modulus value exceeding the test range.

Test under variable distance in certain load

This experiment simulated the sensing optical fiber axial strain changes in different spans of the sinkhole by applying certain load.



Figure 6. The strain change after unloading (GFRP).



Figure 7. The strain change after unloading (Ordinary optical fiber).

The experiment process

The load are applied 2Kg on the ordinary optical fiber and 5Kg on the GFRP optical fiber respectively The experiment simulates the sinkhole span starting from 1 meter to 2.5 meter with 0.5 m interval.

Test data processing and analysis

In order to analyze the change of the sensing optical fiber strain, there is a mechanical analysis about the certain load experiment (Figure 8).

$$\mathbf{2T}\sin\mathbf{\Theta} = \mathbf{G} \tag{7}$$

where:

L - the distance of the fixed point;

 Δ h-the vertical displacement of the loading point;

G-load;

T-the sensing optical fiber axial stretching force;

 Θ - the included angle between the sensing optical fiber and the level.

According to Figure 9, the maximal vertical displacement of the loading point is 55 mm and the minimum distance of the fixed point is 1000mm. under the assumption of small deformation, the hypotenuse is approximately equal to half of the distance of the fixed point, so, the sin θ value is 0.11 and the θ value is 6.30. The hypothesis θ equal to sin θ can be established when the sin θ is small enough.

$$\mathbf{T} = \frac{\mathbf{G}}{\mathbf{26}} \tag{8}$$

Not considering the material factor, the relationship between sensing optical fiber axial stretching force and the included angle is inverse proportion. For ordinary optical fiber, the strain changes from 4.5 m to 5.4 m, corresponding to the fixed point distance changing from 1m to 2.5 m (Figure 10).

For the GFRP optical fiber (Figure 11), analysis of the optical fiber elastic modulus and the friction between the optical fiber and the soil shows that the distance of the fixed point corresponds to the strain change. According to the analysis ,the ordinary optical fiber elastic modulus







Figure 9. Vertical displacement in different sinkhole span.



Figure 10. Strain change in different sinkhole span (Ordinary optical fiber).



Figure 11. Strain change in different sinkhole span (GFRP).

is smaller and the friction is bigger than the GFRP optical fiber, so, its strain change scope is bigger. The change of the sinkhole deformation can be identified in the image by analyzing the optical fiber material characteristics and the load.

Conclusion

In the process of soil void formation and subsequent sinkhole collapse, axial strain and deformation of the optical fiber have good correspondence to the load variation. It is feasible to adopt the fiber-optical sensing technology to monitor the location, size and collapsing process of the void in soil.

Under a certain load, fiber strain corresponds to the size of soil void, but different fiber materials have specific effects on the strain value, which must be understand and choose appropriately.

Thus, the appropriate type of optical fiber or improving the deformation coordination between the soil and the fiber by indirect measurement, will strengthen the response sensitivity. Although the modeling test was carried out on a simplified model, it still demonstrates that the strain characteristics of the optical fiber due to soil void deformation may be a useful tool for predicting sinkhole collapse.

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INDUCED SINKHOLE FORMATION ASSOCIATED WITH INSTALLATION OF A HIGH-PRESSURE NATURAL GAS PIPELINE, WEST-CENTRAL FLORIDA

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Abstract

Induced sinkholes are a known geologic hazard and may be associated with construction activities that cause alteration of ground water flow patterns or induce rapid loads and/or vibrations on karst-affected soils and rocks. This study describes the geophysical and geotechnical investigation of a site in northern Hillsborough County, Florida, where a large diameter underground high-pressure natural gas pipeline was installed utilizing horizontal directional drilling (HDD) methods. Objectives of the investigation were to evaluate the impacts of: 1) pipeline installation on existing ground-collapse features, 2) potential induced ground subsidence and 3) possible effects on water bodies and building structures. The site was investigated utilizing geophysical testing (electrical resistivity), standard penetration test (SPT) borings, and ground vibration monitoring during pipeline construction. In the investigation, subsurface conditions indicative of possible preexisting weakened soil and rock materials associated with incipient raveled zones in overburden soils and soil-filled conduits in limestone bedrock were found in proximity to the pipeline corridor. During the HDD boring and pipeline installation, noticeable ground vibrations occurred, along with formation of several ground settlement/collapse features. The data suggest two mechanisms of induced sinkhole formation: erosion of weak zones in overburden soils by the high pressure drilling mud and/or erosion of weak, soil-filled conduits in limestone bedrock. In addition to current settlement impacts to the property, the investigation found a potential for future ground subsidence associated with undetected eroded and raveled zones that may in the future propagate to the land surface.

Introduction

Induced sinkholes are caused or accelerated by human activities and are associated with two broad conditions:

those triggered by water level declines, typically from ground water withdrawals (pumping), or those related to construction activities (Newton, 1987). In west-central Florida, sinkhole formation and ground subsidence accompanying heavy ground water pumping are common occurrences and are typically associated with rapid declines in the potentiometric surface of the Floridan aquifer. This causes an increase in effective stress over pre-existing zones of weakness, such as soil or rock voids formed by dissolution. Increased pumping can alter the flow regime in the aquifer, increasing flow rates within conduits causing loosening of soil plugs in partiallyfilled cavities in the limestone bedrock and triggering downward raveling of overburden soils. Pumping can induce recharge from the surficial aquifer, destabilizing incipient raveled soil zones in the subsurface.

Sinkhole formation can also be triggered by construction activities such as water impoundment in reservoirs and retention basins, ground loading, ground vibrations from heavy equipment, changes to natural drainage patterns by diversion of stormwater, and drilling of borings and water wells. The mechanisms activating sinkhole formation would include increased ground water recharge and flow to weakened soil zones and bedrock conduits, and abrupt increases in loads and/or vibrations on pre-existing zones of weakened soils and rocks associated with incipient sinkhole conditions.

This paper presents a case history of a geophysical and geotechnical investigation conducted at a site in northern Hillsborough County, Florida. The purpose of the investigation was to evaluate impacts from installation of an underground, 0.9-meter (36-inch) diameter, high-pressure natural gas pipeline across the property. Investigation objectives included evaluation of existing karst subsidence feature(s), potential for induced ground subsidence, and impacts on building structures and water bodies near the property. The study methods included an electrical resistivity survey of the pipeline corridor, subsurface testing by standard penetration test (SPT) borings, and ground vibration monitoring during pipeline installation.

Location and Geologic Setting

The site is located in extreme north-central Hillsborough County, Florida (Figure 1). The subject property is approximately 20 acres in size and is bordered by Hog Island Lake on the southern and eastern sides and vegetated wetland areas on the northern side. The site is generally flat with minimal topographic relief, with ground elevations ranging from approximately 22 meters (71 ft. NGVD) in northwestern portions of the property to 20 meters (64 ft. NGVD) along Hog Island Lake to the south and east, and the fringing wetland areas on the north side. Two large residential structures and associated outbuildings are currently located on the property (Figure 2).

Geology

The subject property lies within the Land O' Lakes Karst Plain (Scott, 2005), which encompasses much of northwestern Hillsborough County, as well as coastal areas of Pinellas, Pasco, and Hernando Counties. The geomorphic province is formed by a series of Pleistocene age marine terraces developed on sandy and



Figure 1. Location Map, Hillsborough County, Florida.

clayey sediments and carbonate rocks of the Miocene age Hawthorn Group and the Oligocene Suwannee Limestone. The project site is located within the Penholoway terrace (Healy, 1975), which formed during retreating sea levels at elevations between 13 and 21 meters (42 and 70 ft.). This terrace has been modified by fluvial and marine erosion, stream and lake deposition, and eolian deposits and further shaped by karst-related landforms including sinkhole lakes, cypress domes, and broad wetland basins. Numerous lakes and swamps are present within and near the project area. These features were created by karst processes resulting in broad



Figure 2. Geophysical Testing and Boring Location Plan showing pipeline easement, building structures, and testing locations.

wetland basins and lakes formed by multiple coalescing sinkhole and subsidence features.

Peninsular Florida is underlain by a thick sequence of Paleogene carbonate rocks that form the Florida platform, which is capped by a thin series of Miocene to Holocene age carbonate rocks and siliciclastic sediments. Important geologic and hydrogeologic units in north-central Hillsborough County are summarized in Table 1. Descriptions of each unit are taken from Arthur et al. (2008), Campbell (1984), and Scott, (1988).

Hydrogeology

Two principal hydrogeologic units are present in the project area (Table 1), the surficial aquifer system and the Upper Floridan aquifer system. The surficial aquifer is hosted primarily by permeable sandy soils within undifferentiated surficial deposits. Clayey soil units within the upper Hawthorn Group, where present, form a confining unit separating the surficial aquifer from the Upper Floridan aquifer, which is hosted primarily in the Suwannee Limestone and deeper limestone formations (Ocala Limestone and Avon Park Formation).

The surficial aquifer is generally unconfined with the potentiometric surface corresponding with the water table, which occurs at depths of less than 1.5 meters (5 ft.) in the project area. The potentiometric surface of the Upper Floridan Aquifer system in the area occurs at elevations of 18 to 20 meters (60 to 65 ft. NGVD). While the Upper Floridan Aquifer is typically confined by low permeability sediments of the Hawthorn group, hydraulic connection with the surficial aquifer often occurs in local areas where the confining units have been removed by erosion or are breached by sinkhole features filled with permeable sandy sediments. Lakes and wetland basins

are common sites of paleo or relic sinkhole activity and provide for hydraulic connection between the surficial and Floridan aquifers.

Karst and Sinkhole Development

In west-central Florida sinkhole formation occurs by two primary mechanisms: cover-collapse and coversubsidence (Sinclair et al., 1985). Buried paleo-sinkholes or paleo-karst structures include ancient sinkhole features that have been buried or filled with younger soils or sediments. They also constitute a geologic hazard since they are subject to reactivation by raveling and further subsidence. The stability of paleo-karst structures varies greatly depending on the degree of consolidation of infilling sediments, the physical connection with cavities and conduits in the limestone formation, and the hydraulic connection with the deeper aquifers. Lakes and wetland basins are commonly related to paleo-sinkhole activity and may serve as recharge areas to the Floridan Aquifer. Paleo-karst structures are extremely common features in the subsurface in west-central Florida (Horwitz and Smith, 2003; Wilson and Shock, 1996).

Pipeline Construction

The gas pipeline consisted of a nominal 0.9-meter diameter (36-inch) steel pipe installed through a horizontal directional borehole located within an easement traversing the northern side of the subject property. The easement is approximately 15 meters wide and 437 meters long (50 by 1,435 ft.) with a general west to east alignment extending from the northwest corner of the site to the eastern property boundary along Hog Island Lake. The easement passes in close proximity to the main residential building and outbuildings (Figure 2). The borehole for the pipeline was completed using horizontal directional drilling (HDD) methods to depths

Table 1. Regional Geologic and Hydrogeologic Units, Northern Hillsborough County.

System	Series	Lithostratigraphic Unit	Lithology	Hydrostratigraphic Unit	
Quaternary	Holocene	Undifferentiated	Very fine to medium grained quartz sand,	Surficial Aquifer System	
	Pleistocene	Sands and Clays	minor silty, clayey and organic soils, local deeper clayey soils and shell beds		
Tertiary	Miocene	Tampa Member: Arcadia Formation (Hawthorn Group)	White to tan, quartz sandy, locally clayey, fossiliferous limestone and dolostone, phosphatic, clayey, locally silicified in up- per portion	Upper Floridan Aquifer	
	Oligocene	Suwannee Limestone	Pale yellow white, sandy, fossiliferous, fine grainstone		

up to 30 meters (100 ft.), to an approximate elevation of -11 meters (-35 ft. NGVD). The entry point for the HDD borehole is located near the northwest corner of the subject property, extending over a horizontal design length of approximately 1,074 meters (3,522 ft.) to the pipeline exit point east of the site and Hog Island Lake.

In addition to the new pipeline, an existing 0.75-meter (30-inch) diameter underground gas pipeline is located just north of the subject property and generally parallels the easement for the new pipeline. Although the construction details and depth of the older pipeline are not known, it was presumed that it was installed using similar HDD methods as with the current pipeline. One concern at the site is an existing ground collapse feature located near the existing smaller gas pipeline (Figure 2). The collapse feature is oval in shape with dimensions of approximately 6 by 9 meters (20 by 30 ft.) extending to a depth in excess of 5 meters (15 ft.). Given the location and morphology of the collapse feature, it is the authors' opinion that it is an induced sinkhole collapse associated with the installation of the existing gas pipeline.

Minimal geotechnical data were collected by the pipeline contractor, consisting of two SPT borings drilled at each end of the pipeline alignment and advanced to depths of approximately 30 meters (100 ft.).

Electrical Resistivity Survey

An electrical resistivity imaging (ERI) survey was conducted over accessible portions of the pipeline corridor and surrounding area to assist in characterizing the general subsurface geology and identify potential anomalous subsurface geological features for further investigation. The ERI survey consisted of four transect lines using up to 112 electrodes at a spacing of 3 meters (10 ft.). Two transects oriented approximately west to east were located within the pipeline corridor, with lengths of approximately 270 and 250 meters (885 ft. and 820 ft.). Additionally, two shorter transects, approximately 128 and 41 meters (420 ft. and 135 ft.) long and oriented perpendicular to the pipeline corridor, were completed in the eastern and western portions of the property. The western transect was located near the western side of the masonry outbuilding and the existing ground collapse feature. The locations of the ERI transects are shown on Figure 2.

The resistivity data were collected using a combined dipole-dipole and inverse Schlumberger electrode array,

and were subjected to inverse modeling to produce two-dimensional resistivity profiles for each transect. The modeled data were then analyzed with respect to identifying anomalous electrical resistivity signatures associated with potential subsurface karst features based on the following criteria:

Columnar patterns of higher resistivity materials extending to the depth of apparent limestone bedrock. These patterns may indicate sand-filled depressions related to in-filled or paleo-sinkhole features or potential zones of soil raveling.

Patterns indicative of localized increased depth of limestone bedrock related to potential paleo-sinkhole features.

The resistivity profiles (Figure 3) were interpreted as showing a surficial layer of higher resistivity sandy soils overlying moderate to low resistivity materials correlated with limestone occurring at approximate depths of 11 to 14 meters (35 to 45 ft.). Two anomalous areas were identified within the central portion of the survey area located north and northwest of the main residential building. The anomalies were characterized by areas of higher resistivity materials at depth representing possible zones of downward raveling sands extending to limestone bedrock. The anomalies were subsequently tested by SPT borings A-1 and A-2.

Geological Conditions

Standard penetration test (SPT) borings were used to investigate subsurface conditions and geophysical anomalies within the pipeline corridor. The borings were conducted using conventional mud rotary drilling methods, in general accordance with ASTM Standard D 1586. Thirteen (13) SPT borings were performed along the alignment of the proposed gas pipeline and advanced to depths ranging from approximately 12 to 34 meters (40 to 110 ft.) below ground surface. The boring locations are shown on Figure 2.

The subsurface geological and geotechnical data were used to construct a geologic profile of the pipeline corridor, depicted in Figure 4. Three generalized subsurface units or soil strata were encountered in the borings:

ERI Transect 1



Figure 3. Electrical Resistivity Profiles.

- Stratum 1 Sand, Sand with Clay, Peat USCS class. = SP, SP-SC, Pt
- Stratum 2 Sand with Clay, Clayey Sand, Sandy Clay USCS class. = SP-SC, SC, CH

Stratum 3 Limestone, variably weathered

Stratum 1 comprises the surficial soil unit at the site and consists of dominantly light-colored fine-grained quartz sand, with localized near surface deposits of peat (1 to 3 ft.) and deeper lenses of sand with clay and clayey sand (Stratum 2). The soil unit has a variable thickness, extending to depths ranging from approximately 7 to 14 meters (22 to 47 ft.) in eastern and central portions of the site to 23 meters (75 ft.) in a boring located near the entry point of the gas pipeline at the northwestern corner of the property. Sandy soils similar in appearance to Stratum 1 were also encountered as localized infilled zones within the limestone bedrock in the eastern portion the property.

Stratum 2 consists of variably clayey sand and minor sandy clay and was encountered as local shallow lenses within the surficial sands, as a deeper persistent soil unit extending to limestone bedrock, and as apparent in-filled zones within the limestone. Limestone bedrock (Stratum 3) consists of light colored (white to gray) fine grained limestone, with local clay fracture fillings and soil in-filled zones. The limestone was encountered at variable depths, ranging from 10 to 19 meters (32 to 62 ft.) in eastern and central portions of the site. The limestone bedrock deepens to the west to depths in excess of 24 meters (80 ft.).

The subsurface soil and rock materials exhibited a variable density and consistency over the depth of the SPT borings. Isolated zones of very loose and very soft soil and rock materials over intervals of 0.5 to 2 meters (1.5 to 6.5 ft.) were encountered in several borings in the western and eastern portions of the site. The weak soils and rock zones occurred within the mid-depth overburden soils and as deeper soft and soil in-filled zones within the limestone bedrock.

During drilling, partial to complete losses of drilling fluid circulation were recorded in 6 of the 13 SPT borings. The circulation losses typically occurred in association with very loose zones within the clayey soil unit (Stratum 2) near the soil/limestone contact, within the upper portion of the limestone formation, or within soil in-filled zones within the limestone bedrock.

The surficial sands and clayey soils (Strata 1 and 2) are correlated with undifferentiated Holocene and Pleistocene deposits. The limestone bedrock correlates





with Suwannee Limestone (Oligocene). A thin section of the Tampa Member of the Arcadia Formation (Miocene) also appears to occur in the upper portion of the limestone unit, but is difficult to differentiate from the underlying Suwannee Limestone (Arthur et al., 2008).

Monitoring of Pipeline Construction

As described, the gas pipeline was installed through a large diameter HDD borehole. HDD is a multi-stage process involving the following phases:

Pilot Hole: Initially, a small diameter pilot borehole is drilled. The borehole orientation is controlled by varying the angle of the drill bit. During drilling, the location of the borehole is surveyed using electromagnetic methods.

Reaming Process: Upon completion of the pilot hole, the borehole is enlarged. Reaming tools with increasing diameters are alternatively pushed and pulled in multiple passes through the borehole until it reaches the final diameter.

Mud Pass: After the final borehole diameter is reached, a mud pass or packer reamer is passed through the directional borehole to clean and remove soil and rock cuttings and to ensure the borehole has been filled with the drilling fluid to allow for a smooth lubricated pull back of the steel pipeline.

Pull Back: The final stage involves pulling the pipeline through the reamed borehole. A weld cap and swivel are welded to the end of the pipeline, which is then attached to the drill string to prevent rotation of the pipeline as it is pulled through the borehole. Depending on the size of the pipe, artificial buoyancy measures may be employed to maintain neutral buoyancy in the pipeline. At the subject property, a vibration or hammer device was apparently utilized to facilitate the installation of the pipeline through the borehole, resulting in noticeable ground vibrations in the area.

Monitoring of site conditions were conducted over the course of the HDD boring and installation of the pipeline. The monitoring consisted of a review of available daily drilling reports provided by the HDD drilling contractor, as well as periodic inspections of the property. Several notable events occurred during completion of the HDD boring and installation of the gas pipeline. These included the formation of several ground settlement/collapse features and associated discharges of drilling mud ("blow-outs"). These features were located within and near the pipeline easement in the northwestern portion of the site (Figure 5). Noticeable ground vibrations also occurred largely during installation of the pipeline within the borehole.

Ground Vibration Monitoring

Ground vibration monitoring was conducted during the HDD drilling and pipeline installation to address concerns regarding potential damage to building structures. Excessive ground vibrations and ground collapses had occurred at a similar HDD boring site in central Pasco County, north of the subject property.

The ground vibration monitoring utilized a remote seismograph system, which measures peak particle velocity, frequency, and air overpressures produced by vibration sources. The system records on a continuous basis in a histogram recording at a rate of 1000 samples per second with a maximum peak particle velocity



Figure 5. Photographs of "blowout" and ground collapse features.

(PPV) recorded every minute. Data are transmitted via a cellular telemetry system. The geophone records vibrations on the longitudinal, transverse, and vertical axes. The seismograph was installed adjacent to the pipeline easement near one of the masonry outbuildings (Figure 2).

Although no specific standards have been established to evaluate ground vibrations, vibration data are often compared to U.S. Bureau of Mines (USBM) criteria for evaluating damage to building structures from blasting in mines and quarries (Siskind et al., 1980). While ground vibrations can be perceived by humans at very low levels (PPV = 0.01 to 0.1 in./sec.), vibration levels required to cause damages to building structures are much higher, ranging from 0.5 in./sec at frequencies of 0.3 Hz to 2.0 in./sec. at 100 Hz. At the subject property, generally low vibration levels were measured during the monitoring period. Maximum daily peak particle velocities (PPVs) ranged from 0.008 to 0.053 in./sec. at frequencies of 0.2 to 100 Hz. The highest ground vibrations appeared to correlate, in part, with installation of the gas pipeline within the HDD boring, which apparently involved use of the hammering device and perceived ground vibrations. However, in each instance the measured ground vibrations were well below USBM criteria for building damage, ranging from 1% to 2% of the limits for the given frequency. However, while standards were not met, neighboring homes felt the vibrations associated with advancement of the pipe and complained of the noise created by the hammering efforts associated with installation of the pipe through the borehole.

Geologic Hazards Analysis Geologic Hazards

Based on local geologic conditions at the site, induced sinkhole activity or ground subsidence is a significant geologic hazard at the subject property. There are numerous examples of induced sinkholes related to ground water pumping in the region, including documented 1964 and 1973 sinkhole occurrences in the vicinity of the Section 21 and South Pasco well fields (Sinclair et al., 1985; Tihansky, 1999). More recently, large numbers of sinkholes developed in 1998 at a property in southwestern Hernando County during development of a large capacity water production well. In 2009 and 2010, multiple sinkholes formed in the Plant City/Dover areas (Hillsborough County) in association with heavy irrigation pumping for freeze protection of strawberry crops. These sinkholes caused substantial damages to private and public buildings and infrastructure.

Sinkhole formation in karst areas can also be triggered by construction activities such as water impoundment in reservoirs and retention basins, loading and ground vibrations from heavy equipment, changes to natural drainage patterns by diversion of stormwater, and drilling of borings and water wells. Examples of construction-related sinkholes are also common in the area. In western Pasco and Hernando counties. sinkholes have frequently formed in stormwater retention basins, typically following heavy rain events. Ground subsidence events have also been known to occur during drilling of water wells and even geotechnical borings. In addition, the authors are familiar with an occurrence of induced sinkhole activity in 2007 during construction of the Land O' Lakes water reuse reservoir. At the site, numerous collapse sinkholes formed during construction of a soilbentonite seepage cutoff wall within a dike associated with the reservoir. The sinkholes likely developed in response to the increased hydraulic loadings imposed by the soil-bentonite slurry on weakened soil zones and voids near the dissolutioned limestone bedrock surface.

Induced Sinkhole Formation

At the subject property, multiple ground settlement/ collapse features or induced sinkholes formed in response to the HDD boring and pipeline installation. The "blow-out" features ranged from approximately 4 ft. to greater than 10 ft. in diameter and were located within or near the pipeline easement in the western portion of the site (Figures 2 and 5). Drilling mud was discharged to the ground in three of the settlement/collapse features indicating a hydraulic connection with the underlying HDD boring and deeper limestone formation.

These induced sinkholes are theorized to have been triggered by increased stresses on preexisting weakened soil and rock materials associated with incipient sinkhole conditions in the subsurface. Based on the SPT borings, such conditions appear to exist as weakened or partially raveled zones within the overburden soils above the limestone bedrock, or as soil in-filled zones within dissolution conduits within the limestone bedrock. These induced sinkholes which formed in association with the previous and current pipeline construction, and the similar collapse events at other HDD boring sites indicate that induced sinkholes should be considered a common geologic hazard associated with HDD drilling and pipeline construction in the region.

Two mechanisms of induced sinkhole formation appear to be occurring at the site, depending on whether the HDD boring was advanced within overburden soils or in limestone. In the western portion of the site, where the HDD boring was advanced through sandy overburden soils, the large diameter borehole entailed the removal of significant amounts of soil materials, which would lead to further weakening of any incipient raveled zones intercepted by the boring. The high fluid pressures and volumes of drilling mud utilized in the drilling would cause significant erosion of the loose soils, enlarging the weak soil zones, and triggering further raveling. The larger of these weak zones eventually propagated upward to the land surface resulting in ground settlement and collapse.

In the central and eastern portions of the site, the HDD boring reached its target depth and was advanced through limestone. Soil-filled dissolution conduits are common features within the Suwannee Limestone, occurring as vertical shafts, pits, and dissolutionally-enlarged fissures that often connect with deeper cavern systems (Yon and Hendry, 1972; Wilson and Shock, 1996). Given the abundance of these features in the region and their presence in the SPT borings at the site, it is probable these structures were encountered during advancement of the HDD boring. The elevated fluid pressures and flow of the drilling mud would cause erosion of weaker zones in the soil-filled conduits, potentially loosening soil plugs near the bedrock surface and triggering raveling of the overburden soils. These conditions could also result in ground settlement or collapse if the raveling propagates close to the land surface.

In addition to the current ground settlement/collapse events at the site, there is an elevated risk of further ground subsidence associated with the HDD boring and pipeline installation. It is important to note that the induced sinkhole features that occurred in association with the HDD boring have established a hydraulic connection between the limestone, the pipeline bore, and the land surface. These connections allowed the drilling mud from the borehole to discharge to the surface during drilling operations, but may have also extended through any overburden soils below the boring and into the limestone bedrock. These weakened soil zones would remain in the subsurface and may trigger future ground settlement as the drill mud dissipates with time.

There is also a probability that additional zones of eroded and raveled soil zones are present in the subsurface that have not yet propagated to the land surface. The subsurface data from the geotechnical investigation are favorable for incipient sinkhole conditions over much of the pipeline corridor. An abrupt increase in depth to limestone bedrock along with zones of weak soils was found in SPT borings located in the northwestern portion of the site. The large wetland basin in the area appears to correspond with the underlying basin feature in the limestone, suggesting the presence of a large paleo-karst structure and associated raveled soil zones in the subsurface. To the east, deeper zones of lowstrength overburden soils and very loose and soft soil in-filled zones in the limestone were found in several borings. Collectively, these data suggest a probability that the HDD boring intercepted weak and raveled zones in the overburden and soil-filled conduits in the limestone. Depending on the degree of erosion, these weakened zones may have developed to the point to serve as potential locations of future ground settlement. In the authors' opinion, the potentially impacted areas would encompass the pipeline easement and potentially affecting building structures on the site.

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COVER-COLLAPSE SINKHOLE DEVELOPMENT IN THE CRETACEOUS EDWARDS LIMESTONE, CENTRAL TEXAS

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Abstract

Sudden cover-collapse sinkhole (doline) development is uncommon in the karstic Cretaceous-age Edwards limestone of central Texas. This paper presents a casestudy of a sinkhole that formed within a stormwater retention pond (SWRP) in southwest Austin. Results presented include hydrogeologic characterizations, fate of stormwater, and mitigation of the sinkhole.

On January 24, 2012, a 11 cm (4.5 in) rainfall filled the SWRP with about 3 m (10 ft) of stormwater. Subsequently, a sinkhole formed within the floor of a SWRP measuring about 9 m (30 ft) in diameter and 4 m (12 ft) deep. About 26.5 million liters (7 million gallons) of stormwater drained into the aquifer through this opening.

To determine the path, velocity, and destination of stormwater entering the sinkhole a dye trace was conducted. Phloxine B was injected into the sinkhole on February 3, 2012. The dye was detected at one well and arrived at Barton Springs in less than 4 days for a minimum velocity of 2 km/day (1.3 mi/day).

Review of pre-development 2-foot topographic contour and geologic maps reveals that the SWRP was built within a broad (5,200 m²; 6 acre), shallow depression bounded by two inferred NE-trending fault zones. Photographs taken during SWRP construction showed steep west-dipping bedrock in the northern SWRP wall. Following collapse of the sinkhole, additional hydrogeologic characterization included excavation to a depth of 6.4 m (21 ft), surface geophysics (resistivity), and rock coring. Geologic materials consisted mostly of friable, highly altered, clayey limestone consistent with epikarst in-filled with terra rosa providing a cover of the feature. Dipping beds, and fractured bedrock support proximity to the mapped fault zone. Geophysics and surface observations suggested a lateral pathway for stormwater flow at the junction between the wet pond's impermeable geomembrane and compacted clay liner for the retention pond. The collapse appears to have been caused by stormwater down-washing poorly consolidated sediments from beneath the SWRP and into a pre-existing karst conduit system.

Mitigation of the sinkhole included backfill ranging from boulders to gravel, a geomembrane cover, and reinforced concrete cap. Additional improvements to the SWRP included a new compacted clay liner overlain by a geomembrane liner on the side slopes of the retention pond.

Introduction

Karst is a terrain with distinctive hydrology resulting from the combination of high rock solubility and welldeveloped solution channel porosity underground (Ford, 2004). Karst terrains and aquifers are characterized by sinking streams, sinkholes, caves, springs, and an integrated system of pipe-like conduits that rapidly transport groundwater from recharge features to springs (White, 1988; Todd and Mays, 2005). Sinkholes (also known as dolines) have long been characteristic of many karstic terrains in many areas of the world (White, 1988; Gunn, 2004). Caves and sinkholes are a very characteristic and common occurrence in the Cretaceousage limestones of Texas in the Edwards Plateau and Balcones Fault Zone (Kastning, 1987). The purpose of this paper is to document the development and mitigation of a cover-collapse sinkhole in the Edwards Group limestones. This sinkhole occurred in the Arbor Trails retail development stormwater pond and is referred to as the Arbor Trails Sinkhole (ATS). This case study will lead to insights into how to avoid activating or inducing sinkhole collapse in the future.

Sinkholes

A broad discussion of sinkholes is beyond the scope of this study, but some introduction to cover-collapse sinkholes is helpful. Sinkholes can be generally defined as "a natural enclosed depression found in karst landscapes" (Williams, 2004). The mechanisms of sinkhole development are often multi-faceted and include dissolution, collapse, suffusion (winnowing or downwashing), and regional subsidence. These mechanisms produce sinkholes described broadly as either a solution sinkhole, or a collapse sinkhole.

A typical limestone sinkhole develops as a depression formed by the slow process of dissolution forming a broad bowl with a gentle slope. Solution sinkholes usually have soil cover and eventually the floor will collapse rapidly due to gravitational forces following continued dissolution, down-washing of soils, and upward stoping of the cavern (void) ceiling. Sudden collapse, due to mechanically weakened unconsolidated (usually clay-rich) sediments, can then down-wash through solution pipes in the bedrock. These covercollapse sinkholes produce steep-sided slopes and are cylindrical in geometry (Williams, 2004). Granular sediments have a different morphology and can form more slowly (Denton, 2013, written communication). Cover-collapse sinkholes generally refers to soil cover, and not collapse of mappable geologic units (Veni, 2012, written communication). Cover-collapse sinkholes are also called dropout dolines, or simply collapse dolines (Williams, 2004; White, 1988).

Development of sinkholes is related to the ability of water to flow through karst rocks and discharge to springs (Williams, 2004). Recharge water dissolves the rock over geologic time, which allows more water to flow, and therefore is a self-reinforcing mechanism speeding up the process. Significant dissolution is thought by some to occur within 9m (30 ft) of the surface, leaving behind a highly corroded and permeable zone termed epikarst (Williams, 2004).

The collapse of sinkholes is clearly a natural phenomenon. However, Beck and Sinclair (1986) describe how humans can accelerate the process and "activate" or "induce" a collapse sinkhole. This occurs by increasing the infiltration of water, which speeds up the piping of unconsolidated materials, creating a large void and caves in the soil or regolith, resulting in collapse.

Sinkhole development in the karstic areas of Texas is a common occurrence and is documented in Kastning (1987), but cover-collapse sinkholes are uncommon. Many studies of the eastern United States document cover-collapse sinkholes leading to structural or other environmental problems (Newton and Tanner, 1987). However, the authors are not aware of any sudden covercollapse of sinkholes resulting in significant structural damage in the karstic Edwards, although examples may exist in areas with thick soils. Instead, the Edwards has many relatively stable sinkholes that do not cause major structural problems due to collapse. These stable collapse sinkholes are more accurately described as cave-collapse, or bedrock-collapse, sinkholes related to the intersection of older phreatically-formed caves with the land surface due to erosion of the overlying strata. Other stable sinkholes are formed by more recent vadose dissolution (often with a combination of collapse) and are directly linked to the current surface hydrology.

The absence of sudden cover-collapse sinkholes in the Edwards Group is due primarily to the lack of thick soil cover throughout central Texas as the karst bedrock is often exposed directly at the surface. Other factors include the semi-arid climate and the deep water table conditions.

Setting

The Edwards Aquifer system lies within the Mioceneage Balcones Fault Zone (BFZ) of south-central Texas and consists of an area of about 10,800 km2 (4,200 mi2). Groundwater from the Edwards Aquifer is the primary source of water for about two million people, plus numerous industrial, commercial, and irrigation users. The Edwards Aquifer system also supports 11 threatened or endangered species, aquatic habitats in rivers of the Gulf Coastal Plain, and coastal bays and estuaries. Hydrologic divides separate the Edwards Aquifer into three segments. North of the Colorado River is the Northern segment, and south of the southern hydrologic divide near the City of Kyle is the San Antonio segment (Figure 1). The Barton Springs segment is located between these two larger segments. The Shops at Arbor Trails is the development where the subject sinkhole developed, and is located within the recharge zone of the Barton Springs segment of the Edwards Aquifer (Figure 1).

Development of the Edwards Aquifer was influenced significantly by fracturing and faulting associated with Miocene-age tectonic activity and subsequent dissolution of limestone and dolomite units by infiltrating meteoric water (Sharp, 1990; Barker et al., 1994; Hovorka et al., 1995; Hovorka et al., 1998; Small et al., 1996). Development of the aquifer is also thought to have been influenced by deep dissolution processes along the saline-fresh water interface, what is known as hypogene speleogenesis (Klimchouk, 2007; Schindel et al., 2008).

The majority of recharge to the aquifer is derived from major stream channels originating on the contributing zone, located upgradient and primarily west of the recharge zone. Water flowing onto the recharge zone sinks into numerous caves, sinkholes, and fractures along numerous (ephemeral to intermittent) losing streams. For the Barton Springs segment, Slade et al. (1986) estimated that as much as 85% of recharge to the aquifer is from



Figure 1. Location map of the study area. Indicated are the Brush Country well (BC well) and a USGS stream gage station on Williamson Creek.

water flowing in these streams. The remaining recharge (15%) occurs as infiltration through soils or direct flow into recharge features in the upland areas of the recharge zone (Slade et al., 1986). More recent water balance estimates of the Barton Springs segment suggest that more water could be recharged in the upland or intervening areas (Hauwert, 2009; Hauwert, 2011; Hauwert, 2012).

The Edwards Aquifer is inherently heterogeneous and anisotropic, characteristics that strongly influence groundwater flow and storage (Slade et al., 1985; Maclay and Small, 1986; Hovorka et al., 1996 and 1998; Hunt et al., 2005). The Edwards Aquifer can be described as a triple porosity and permeability system consisting of matrix, fracture, and conduit porosity (Hovorka et al., 1995; Halihan et al., 2000; Lindgren et al., 2004) reflecting an interaction between rock properties, structural history, and hydrologic evolution (Lindgren et al., 2004). In the Barton Springs segment groundwater generally flows from west to east across the recharge zone, converging with preferential groundwater flow paths subparallel to major faulting, and then flowing north toward Barton Springs.

Numerous tracer tests have been performed on portions of the Edwards Aquifer demonstrating that rapid groundwater flow occurs in an integrated network of conduits discharging at wells and springs (BSEACD, 2003; Hauwert et al., 2004; Johnson et al., 2012). In the Barton Springs segment these flow paths are parallel to the N40E (dominant) and N45W (secondary) fault and fracture trends presented on geologic maps, indicating the structural influence on groundwater flow. Rates of groundwater flow along preferential flow paths, determined from dye tracing, can be as fast as 11.3 km/day (7 mi/day) under high-flow conditions or about 1.6 km/day (1 mi/day) under low-flow conditions (Hauwert et al., 2002).

Arbor Trails Pre-Development Site Characterization and Planning

The 0.3 km² (72-acre) property was developed in accordance with City of Austin's Land Development Code and the State of Texas requirements (Chapter 213 Edwards Rules). These requirements include geologic and environmental assessments, and reduction of pollution in stormwater leaving the site. The City of Austin has the most stringent requirements (so called "SOS Ordinance") that limit impervious cover and set nondegradation standards for the treatment of stormwater
on the Edwards Aquifer recharge zone. To achieve this standard, a variety of water quality measures, including construction of Storm Water Retention Ponds (SWRP) are required for development sites. Within the Edwards Aquifer recharge zone SWRPs are a type of permanent water-quality control designed to capture stormwater runoff and sediment so that sediments and other contaminants are not carried further downstream or into the Edwards Aquifer. The failure of a SWRP permits sediment and contaminated stormwater to leave a site and likely enter the aquifer.

Both the State and the City permitting processes stipulate that a karst survey be completed to identify and evaluate all karst recharge features. In addition to the State permitting, the City requires an environmental assessment that identifies any critical environmental features such as karst recharge features, springs, and wetlands. From 1994 to 2006, several development permit applications were submitted for the study property resulting in numerous environmental and geologic assessments. Beside the completion of an site-specific environmental and geologic assessments provided in 1994 and 2004, respectively, at least two phase one environmental assessments were prepared to address hazardous material and general environmental concerns (Kleinfelder, 2005).

In 2004 a karst survey and geologic assessment was completed by HBC/Terracon (2004). The geologic assessment identified three small and minor solution and depression features (S1-S3) in the northeast portion of the property and also identified one mapped fault zone on the property (Figure 2). The fault zone and the geologic units are consistent with the geologic map of Small et al., 1996. The



Figure 2. Predevelopment topographic map. Basemap is USGS Oak Hill Quadrangle (10-ft contours in brown). Geologic information from HBC/Terracon (2004). Geologic units and faults are consistent with Small et al., 1996. Black lines are City of Austin 2-ft topographic contours dated 1981, prior to major highway (MoPac). Contours create a depression centered around the SWRP (shown as dashed lines).

three features were evaluated and scored as sensitive (i.e., they could be pathways for contamination) in the report, but were not considered significant recharge features since they had a small surface catchment area. The fault zone had no surface expression observed and was located based upon published maps (Small et al., 1996). The fault was not scored in the report (HBC/Terracon, 2004) as it was inferred from the map alone. The geologic assessment concluded that, "Due to the lack of any significant recharge features observed on the site, the potential for fluid movement to the Edwards Aquifer beneath the site is considered very low" (HBC/Terracon, 2004).

As part of the site permitting processes, City staff evaluated the findings of these assessments and conducted follow-up field verification of karst and critical environmental features described in the reports. This resulted in an additional karst survey by City staff. None of the assessments or followup site verification investigations identified significant recharge features on the study site, or a large depression in the vicinity of the ATS. City staff were not notified of any subsurface voids encountered during construction.

Review of topographic contours from the City of Austin 2-ft contour maps dated 1981 prior to MoPac (Loop 1) reveals a very shallow and large (5,200 m²; 6 acre) depression centered on the SWRP (Figure 2). The contours agree with an even more subtle depression on the 10-ft contour USGS Quadrangle Map. The area appears well drained from the aerial as no ponded features are evident, and hardwood trees are present. However, the subdued nature of the feature and the subsequent disturbance from the highway that bisected the eastern portion of the depression would make detection of the feature in the field difficult.

As part of the site engineering studies, geotechnical cores and borings were conducted throughout the site. Preliminary geotechnical studies include 6m (20-ft) deep cores that were collected near the ATS (B-8 and B-9; Figure 2). The bores extended the same depth as the final SWRP excavation depth. Both cores returned rock quality designation (RQD) of very poor to incompetent rock. Both cores indicated loss of fluids within the first 3m (10 feet) and solution channels and small voids (HBC/Terracon, 2005), consistent with epikarst.

The location of the SWRP for the Arbor Trails development is shown in Figure 3. The purpose of the

SWRP is to capture storm runoff from impervious areas (buildings and parking lots) and then irrigate vegetative areas with the stormwater throughout the property. The SWRP consists of two water quality controls; a geomembrane-lined wet pond inset within a compacted clay-lined retention pond. The wet pond has a forebay and main permanent pool area that are separated by a berm. The wet pond was constructed for aesthetics within the retention basin. The retention pond has its capture volume above permanent pool elevation for the wet pond. The capture volume for the retention pond extends up 1.8 m (6 ft) onto the slope areas of the basin. The retention pond is the actual permitted waterquality control structure for the surrounding shopping center. During a rain event stormwater captured by the retention basin is held and then irrigated on vegetated areas throughout the property within 72-hours.

Hydrologic Conditions and Sinkhole Collapse

Prior to collapse of the ATS, central Texas had been experiencing a severe drought. Beginning in late January, rainfall and subsequent recharge brought the aquifer out of drought conditions.

On January 24, 2012, an 11 cm (4.5 in) rainfall event occurred in the area of the Arbor Trails development filling the SWRP with about 3 m (10 ft) of water (Figure 4). On January 25, 2012, maintenance crews noticed the pond was draining, and that a sinkhole had developed (Figure 5). The size of the sinkhole was about 9 m (30 ft) in diameter and 4 m (12 ft) deep. About 26.5 million liters (7 million gallons) of storm water drained into the aquifer through this opening.

A significant increase in turbidity at Barton Springs is associated with the late January (and March) rainfall. These types of increases are relatively common in this karst system. Barton Springs/Edwards Aquifer Conservation District (District) staff observed the runoff and recharge into swallets (Brodie Cave) within nearby tributaries of Slaughter Creek from the same rainfall event that created the ATS. It was noted that the stormwater entering those features was very turbid. Accordingly, the jump in turbidity cannot be attributed to the failure of the SWRP.

Sinkhole Characterization Studies

Following the collapse, the sinkhole was further characterized by excavation, surface geophysics, and



Figure 3. Detailed site map with key elements of the stormwater retention pond (SWRP), sinkhole location, and 2012 geophysical lines and boreholes.



Figure 4. Photograph of sinkhole, all photos facing north. A) photo taken the day the sinkhole was observed (credit Heather Beatty, TCEQ). B) Photo taken two days after collapse and prior to excavation. Note the limestone beds are dipping to the west.



Figure 5. Photograph locations indicated in Figure 4. A) Photo during construction of SWRP showing west-dipping beds in the northern wall of the forebay (photo credit Andrew Backus, 4/2/2006); B) Photo of the northern wall of the sinkhole taken two days after collapse and prior to excavation.

borehole (core) drilling by ACI Consulting (Austin, Texas). Prior to those studies the District and City of Austin (CoA) conducted the dye tracing studies. The ATS was excavated to a total depth of 6.4 m (21 ft) (Figure 6). Most of the excavated geologic material in the sinkhole consisted of friable, highly altered (weathered), clayey limestone fragments consistent



Figure 6. Sketch of sinkhole after excavation (by Mike Warton of ACI Consulting).

with terra rosa and regolith filling the epikarst zone. Very little competent bedrock was encountered in the excavations. Solution fractures striking to the north, and west- dipping limestone beds in the sinkhole and in the northern retaining wall, were observed (Figure 5). Geotechnical and geologic information of the bedrock adjacent and within the ATS reveal highly fractured and steeply dipping bedrock suggesting the ATS developed proximal to a fault zone.

Geophysics

The nature of collapse suggested the possible existence of a significant subsurface void allowing the structurally unstable material to further collapse into a void of unknown dimensions. To assess the void and assure structural stability for equipment and workers safety, a mechanism for subsurface evaluation was needed. Based on an initial review of the collapse, ACI proposed a geophysical approach. ACI uses geophysics on numerous karst features and the findings are validated by geotechnical borings and subsequent construction activities. In conjunction with the client and the regulatory authorities, a geophysical electrical resistivity array was designed in conjunction with Round Rock Geophysics Inc. (Round Rock, Texas) to evaluate the shallow surface for anomalies and take a deeper look at the subsurface. Six arrays (4 E-W, 2 N-S) were conducted to evaluate conditions near the void and assess the surrounding area. The second bay (permanent pool) of the pond was not accessible as it was being used as a backup water quality control for development. For the array, metal spikes were driven into the ground to a depth of 20 cm (8 in) at a separation distance that is predetermined based on desired resolution and survey depth. As this investigation was designed to evaluate the subsurface for the collapse geometry and to assure worker safety, a moderate spacing was chosen. Probe

spacing on lines 1 and 2 was 1.5 m (5 ft), which allowed for moderate penetration depth (18 m, 60 ft) and a resolution on the order of one meter (3 ft). Other survey lines had spacing on the order of 2.1 m (7 ft), reducing resolution, but increasing the depth to over 24 m (80 ft). Each probe is connected to an electrical control, data recorder, and a 12-volt battery. Each probe alternated acting as an electrical source and receiver. The electrical pulses were recorded and the electrical energy loss recorded and the results are illustrated in Figure 7.



Figure 7. Resistivity profile from lines 1 and 2 (shown on Figure 3). The sinkhole was located between these two lines. Note the interpretation of water infiltration. This is based upon the resistivity data and the voids observed in the compacted clay material of the retention pond.

Since "resistivity" is a relative measure, two geotechnical borings (B-1 and B-2) were drilled adjacent to the sinkhole to physically evaluate the subsurface and calibrate the geophysical model. Based on the borings, warmer (red) colors representing higher resistivity were determined to be relatively competent (crystalline) limestone. Cooler blue colors representing lower resistivity (high conductivity) were determined from Boring 1 to be wet to saturated clay-filled fractured rock. Boring 2 had poor recovery also suggesting highly fractured rock.

Activation of Collapse

Small voids observed in the compacted clay liner of the retention pond adjacent to the sinkhole, and in the western side of the SWRP, suggest the most likely pathway for water was around the geomembrane liner. These field observations along with the geophysics and other data suggest that water from the SWRP was bypassing the impermeable synthetic liner and infiltrating through the compacted clay liner (Figure 7). The infiltrating water is thought to have flowed within the observed wet and saturated clay-filled rock below the voids in the clay liner. Other interpretations of pathways beneath the liner are possible. Ultimately the infiltrating water carried the finer interstitial clays and sediment into underlying voids. The down-washing created shallower voids and along with a significant hydrostatic load of the ponded stormwater, resulted in a collapse of the relatively weak cover material and development of the sinkhole.

Sinkhole Recharge and Groundwater Flow

Dye-trace studies are an effective means to determine the path, velocity, and destination of groundwater in a karst setting. A dye trace was performed to better understand flow in the area and test which groundwater basin and, therefore springshed, the ATS was developed within. The results will help scientists understand the fate of the stormwater in the ATS, and also how future contaminant spills along MoPac, a major highway adjacent to the study site, will move.

A dye-trace study was conducted in the ATS by the District and the CoA. District staff injected 7.4 kg (16.3 lbs) of Phloxine B dye into the sinkhole on February 3, 2012 (Figure 8). The dye was detected at one well and Barton Springs with a minimum velocity of 2.1 km/day (1.3 mi/day). Results of the trace confirms that the ATS is within the Sunset Valley groundwater basin as previously defined by Hauwert et al. (2004) (Figure 9). Similar to



Figure 8. Phloxine B dye injection at Arbor Trails sinkhole. Dye was injected on February 3, 2012. A mass of about 7 kg (16 lbs) was mixed in a trash can and then gravity injected via a hose and polyvinyl chloride (PVC) pipe using water from an adjacent wet pond.

so many karstic features in the area, the results indicate that the sinkhole is well-integrated into the karstic conduit system of the aquifer.

Sinkhole Mitigation and SWRP Improvements

An engineered closure design by Bury + Partners (Austin, Texas) was reviewed and approved by the City and State to mitigate the sinkhole. The plan consisted of graded fill interlayered with filter fabric (Figure 10). Large rock (> 15 cm, >6 inch) filled the base and was overlain by7-12 cm (3-5 in) gravel, then overlain by 3-8 cm (1-3 in) gravel, and capped with 3 cm (1 in) gravel. A vapor barrier lined the top of the gravel and a reinforced concrete slab was poured on the top and anchored into the splitter box. A compacted clay liner was installed over the concrete followed by a geomembrane liner, both of which covered the entire SWRP (Figure 11).

In addition to the closure of the sink, the owners of the site made significant improvements to the entire SWRP



Figure 9. Map of results from the Arbor Trails dye trace. Pink circles indicate positive detections (very high confidence, both labs) of Phloxine B. White circles are wells with tentative detections (single detections from EAA lab), and solid black circles are locations with non-detects (both labs). Dashed pink line represents estimated flow route and is coincident with the "Sunset Valley Flow Route" defined by Hauwert et al., 2004. Small gray circles are existing water-supply wells. Light gray potentiometric lines are from February 2002 high flow conditions (10-ft contour intervals). Groundwater basins are defined in Hauwert et al., 2004.

to prevent future leakage and sinkhole development (Figure 11). Existing geomembrane liner was replaced and extended 30 cm (1 ft) above the maximum water level of the retention pond (previously the liner only existed for the wet pond). The subgrade underneath the geomembrane liner within the retention pond was replaced with new high quality compacted clay liner and 0.3 m (1 ft) protective soil and grass cover installed over geomembrane line. All masonry walls in the SWRP were grouted and sealed to prevent leakage.

Discussion

Figure 12 illustrates a conceptual hydrogeologic model of the cover-collapse sinkhole at the AST. A broad shallow depression is indicative of a solution sinkhole (Figures 2 and 12A). Evidence of a fault zone include fractures and dipping beds at the site (Figures 4 and 5). Geotechnical borings revealed highly fractured and altered epikarst rock within the SWRP. The SWRP removed about 6 m (20 ft) thick horizon of terra rosa-filled epikarst that likely acted as a mantle of poorly consolidated material



Figure 10. Photographs during sinkhole mitigation. A) Boulders and coarse fill and filter fabric; 5/2/12, B) graded cobble to gravel fill; 5/7/12, C) Gravelfilled sinkhole and filter fabric; 5/9/12, D) Reinforced concrete cap and blue vapor barrier; 5/10/12.

over a fractured and dissolved karstic fault zone (Figure 12B). Hydrostatic loading and stormwater flow around the geomembrane liner and through the epikarst zone allowed down-washing of sediments along solution pipes (Figure 5), and upwards stoping of the void ceiling at depth. Sudden failure occurred as mechanically weak sediments were down-washed through solution pipes in the bedrock (Figures 5 and 12C). Dye tracing established the sinkhole is well-integrated into the aquifer conduit system (Figure 9). The sinkhole was mitigated with graded fill, geomembranes, and a concrete slab. Improvements to the SWRP included extending the liner above the high-water elevation (Figures 11 and 12D).

Under the current development process it is unlikely that the regulators or developers of the area in which the sinkhole occurred would have recognized the risk associated with the location of the SWRP, or predicted the failure. Only after compiling all the information does it become clear that human activities (placement of the SWRP on the sinkhole) activated the sinkhole collapse. Part of the challenge is that the land development process in the karstic Edwards Aquifer has inherent problems of communication between geologists, engineers, consultants, and owners over the life of a project. For example, sites are fully designed and engineered, and then the geologic assessment occurs, resulting in little flexibility in site planning. Likely the SWRP was located precisely in the lowest portion of the property, which makes sense from a engineering standpoint. But in this case the low elevation was a



Figure 11. A) Looking east from the splitter box showing new compacted clay liner overlain by new geomembrane. B) Looking south at the stone splitter box and the finished SWRP after significant rainfall event. New soil and vegetation cover in place over geomembrane in SWRP; 7/11/12. Note the sinkhole was located in front of the splitter box.

covered sinkhole. In addition, geotechnical studies occur without the input from geologists surveying for karst features. Finally, geologists are not required to inspect the SWRP excavation during its construction. Despite these problems inherent in the development process, the studies and site remediation were a model of communication, transparency, and cooperation among the various regulators, scientists, engineers, and owners. All of these parties have a goal to understand the problem and provide the best solution.

Conclusions

This case study documents that cover-collapse sinkholes can develop in the central Texas Cretaceous karst system. In this case the cover is a thick horizon of terra rosa infilling of a shallow epikarst zone. In addition, this

A) Solution Sinkhole: Pre-development





Figure 12. Conceptual hydrogeologic model of sinkhole in four stages: A) Pre-SWRP development, B) SWRP and sinkhole activation, C) cover- collapse, and D) mitigation.

study confirms how human activities, superimposed upon natural karst features, can activate a sinkhole collapse. Dye tracing revealed how wellconnected these features can be with the aquifer system. However, these types of occurrences can be avoided if geologists and engineers are aware of the potential risks associated with SWRPs initiating sinkhole collapse. To reduce the risk of future SWRP failures, studies should be performed beyond current standards for areas impounding water, such as an SWRP. Additional studies could include detailed mapping, topographic surveys, traditional karst surveys, geophysics, and additional geotechnical borings (extending below the final grade) focused around a potential location of an SWRP. Excavations should be inspected periodically by geoscientists and engineers during construction looking for features that could contribute to sinkhole initiation.

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SALT KARST AND COLLAPSE STRUCTURES IN THE ANADARKO BASIN OF OKLAHOMA AND TEXAS

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Abstract

Permian bedded salt is widespread in the Anadarko Basin of western Oklahoma and the Texas Panhandle, where partial or total dissolution of the shallowest salt in some areas has resulted in subsidence and/or collapse of overlying strata. Groundwater has locally dissolved these salts at depths of 10–250 m. The distribution (presence or absence) of salt-bearing units, typically 80–150 m thick, is confirmed by interpretation of geophysical logs of many petroleum tests and a few scattered cores. Salt dissolution by ground water is referred to as "salt karst."

Chaotic structures, collapse features, breccia pipes, and other evidence of disturbed bedding are present in Permian, Cretaceous, and Tertiary strata that overly areas of salt karst. The dip of Permian and post-Permian strata in the region normally is less than one degree, mainly towards the axis of the Anadarko Basin. Where strata locally dip in various directions at angles of 5–25 degrees or more, and underlying salt units show clear evidence of dissolution, these chaotic dips must result (mostly, if not totally) from subsidence and collapse into underlying salt-dissolution cavities.

Gypsum karst and resultant collapse of overlying strata have been proposed in many parts of the Anadarko Basin. However, the gypsum beds typically are only 1–6 m thick and more than 100 m deep, and cannot contribute to disruption of outcropping strata—except where they are within 10–20 m of the surface.

Typical areas of disturbed bedding comprise several hectares, or more, with outcrops of moderately dipping strata—as though large blocks of rock have foundered and subsided into large underground cavities. Other examples of disturbed bedding are small-diameter breccia pipes, or chimneys, that extend vertically up from salt-karst cavities, through several hundred meters of overlying strata. The best evidence of these chimneys are collapsed blocks of Cretaceous strata, chaotically dropped some 50 m, or more, that are now juxtaposed against various Permian formations on the north flank of the Anadarko Basin. Any study of surface or shallow-subsurface geology in the Anadarko Basin must consider the influence of subsurface salt karst on the structure and distribution of overlying rocks.

Introduction

The current study summarizes years of investigations of salt karst and resultant collapse features in and around the Anadarko Basin of western Oklahoma and the Texas Panhandle. These investigations have involved integrated studies of: 1) the subsurface distribution and thickness of Permian salt beds; and 2) field studies to identify areas where outcropping strata are disrupted and disturbed.

Subsurface studies have been carried out mainly by recognition of salt and associated strata on electric logs (also known as "geophysical logs") of oil and gas tests, as well as examination of several cores of salt units in the basin. Identification of evaporites and associated rock types on electric logs is well established (Alger and Crain, 1966), and I have carried out many studies using various types of well logs to identify, correlate, and map salt and gypsum beds in the subsurface—some of the studies are in public documents (Johnson, 1967, 1981, 1989b, 1993), and many others are in consulting reports. Also of special value for this study are the cross sections of Permian evaporites in the Anadarko Basin by Jordan and Vosburg (1963).

In the Anadarko Basin, Permian strata typically are gently dipping or horizontal, with dips normally being less than 10 m/km (less than one degree) towards the axis of the basin. Therefore, where dips are several degrees, or more, and particularly where strata dip chaotically in different directions within short distances, it is most likely a result of dissolution of underlying Permian evaporites (salt and gypsum) and collapse of younger strata into the solution cavities. In most areas the gypsum beds are 1–6 m thick, so their dissolution would not normally disrupt overlying rocks, except where the gypsum bed(s) are less than about 20 m below the land surface. On the other hand, salt units typically are 50–150 m thick, and salt-dissolution cavities can be

quite large and can result in collapse of several hundred meters of overlying strata.

Four examples of salt dissolution and collapse are described in this report to show the geographic range of salt karst and resultant collapse in the Anadarko Basin. These examples are in Beckham, Washita, and Beaver Counties, Oklahoma, and in Hansford County, Texas (Figure 1).

Geologic Setting of Anadarko Basin

The Anadarko Basin is the deepest sedimentary and structural basin in the interior of the United States (Johnson and others, 1988; Johnson, 1989a). Paleozoic sedimentary rocks are as much as 12,000 m thick along the axis of the basin, and Permian strata (which contain the salt units) are as much as 2,100 m thick. Outcropping strata in the basin are predominantly Permian, Tertiary, and Quaternary in age, with some scattered small outliers of mostly collapsed Cretaceous rocks.

The basin is bounded on the south by the Wichita and Amarillo uplifts (Figure 1), and on the east and west by the Nemaha uplift and the Cimarron arch, respectively,



Figure 1. Map of Anadarko Basin in western Oklahoma and Texas Panhandle, and dissolution limit of areas underlain by the Flowerpot, Blaine, and/or Yelton salts.

both of which are outside the region under investigation. The northern shelf of the basin extends across northern Oklahoma and much of western Kansas. The basin is asymmetrical, with the axis located close to its south flank.

Following a Late Cambrian through Mississippian epeirogenic episode, the basin underwent a period of orogenic activity when the Wichita–Amarillo uplift was thrust up and the adjacent Anadarko Basin subsided to receive nearly 5,500 m of Pennsylvanian-age clastics and carbonates. This was followed by a late epeirogenic episode that began in Permian time and has persisted till today.

Most Permian sediments in the Anadarko Basin are redbeds, evaporites, and marine carbonates. They were deposited mainly in fairly shallow water, although some of the redbeds are of deltaic, aeolian, or alluvial origin. Evaporites include anhydrite (gypsum at and near the outcrop), salt (halite), and variable mixtures of salt and shale; potash salts and other evaporites have not been found in the basin.

The principal evaporite units involved in this study are, in ascending order, the Flowerpot salt, the Blaine Formation (gypsum/anhydrite and salt), and the Yelton salt (Figure 2). These units have been grouped into the Beckham evaporites by Jordan and Vosburg (1963), and the region underlain by salt in these units is shown in Figure 1. The total thickness of the salt-bearing Beckham evaporites is as much as 150–220 m along the axis of the Anadarko Basin in Beckham and Washita Counties, Oklahoma, where all three of the evaporite units contain significant salt deposits (Johnson, 1963, 1976; Jordan and Vosburg, 1963).

Salt Karst

Salt (halite, NaCl) is extremely soluble in fresh water. Halite solubility in water is 35% by weight at 25°C, and it increases at higher temperatures. The four basic requirements for dissolution of salt and development of salt karst, are: 1) a deposit of salt against which, or through which, water can flow; 2) a supply of water unsaturated with NaCl; 3) an outlet whereby the resulting brine can escape; and 4) energy (such as a hydrostatic head or density gradient) to cause the flow of water through the system (Johnson, 1981). When all four of these requirements are met, dissolution of salt can be quite rapid, in terms of geologic time.



Figure 2. Cross sections showing dissolution of Permian salt units in eastern Beckham and western Washita Counties, Oklahoma. Upper stratigraphic cross section (Johnson, 1967, Plate II) and lower structural cross section (Johnson, 1963) are along the same alignment.

Permian salt deposits in the Anadarko Basin have been dissolved locally by ground water, and this is still going on, as attested by several natural springs that emit brines formed by dissolution of the salt on the north and south flank of the Anadarko Basin in Oklahoma (Johnson, 1981). Most salt karst in the Anadarko Basin occurs in the Yelton, Blaine, and Flowerpot salts (Beckham evaporites), because these are the shallowest salts; the depth to the top of these salts typically ranges from 10 to 350 m below the present land surface (Figure 2). The present-day depth to salt-dissolution zones ranges from 10-250 m.

Collapse Structures

The normal dip of strata in the Anadarko Basin is less than one degree (less than 10 m/km) towards the axis of the basin. However, dissolution of salt has resulted in a number of collapse structures, and in places underlain by salt karst the overlying strata have subsided, settled, or collapsed into the underground cavities (Figure 2). This has resulted in disturbed bedding in outcropping rocks. Disturbed bedding and collapse structures caused by salt karst in the Oklahoma portion of the Anadarko Basin can be seen not only in outcrops of overlying Permian units (the Cloud Chief, Doxey, and Elk City Formations), but also in the large number of chaotic blocks of Cretaceous strata that are scattered from northern Washita County northward across much of northwestern Oklahoma (Stanley, 2002; Johnson and others, 2003; Fay, 2010; Suneson, 2012).

Early field studies in western Oklahoma have described the erratic dips of outcropping strata. Gould (1902) was the first to describe dips of 20 to 40 degrees in various directions, even within small areas. He ascribed these erratic structures to dissolution in underlying gypsum beds (probably those in the Blaine Formation). Subsequent workers made similar field observations, and also attributed the chaotic structures to gypsum dissolution and collapse. It is now clear that gypsum dissolution is not the cause of these chaotic structures, except around the fringes of the Anadarko Basin where gypsum beds are within 10–20 m of the land surface.

Gypsum beds (or anhydrite at depth) do underlie most parts of the Anadarko Basin, but they are too thin and too deep in most areas for their dissolution to cause disrupted bedding or collapse of Cretaceous strata. Gypsum/ anhydrite beds in the Blaine Formation are 1-6 m thick, but typically they are at depths of 50-500 m. The only other unit with gypsum/anhydrite more than 2 m thick in the basin is the Cloud Chief Formation: the basal gypsum, which is up to 30 m thick in eastern Washita and southeastern Custer Counties, thins sharply to the west and is only 1-4 m thick and is 50-150 m deep in most other parts of the basin. Clearly these two gypsumbearing units are too thin and too deep to contribute to the extensive areas of disrupted outcropping strata, although they may cause subsidence and collapse where they are only about 10-20 m deep.

Recognition that the collapse structures were due to salt dissolution and collapse (not gypsum dissolution) was made in 1963 when Johnson (1963) noted: "Where the Yelton salt is known to be present in subsurface,

outcropping strata in the overlying Cloud Chief, Doxey, and Elk City are undisturbed and dip at angles of but 1 or 2 degrees. At several places where the salt is known to be absent... the surface beds are highly disturbed and dip in all directions at angles up to 25 degrees."

I later served on the thesis committees of several University of Oklahoma students who were doing field mapping in Beckham and Washita Counties, and asked them to make maps showing locations within their study areas where surface rocks were undisturbed or disturbed. The work by these students (Smith, 1964; Richardson, 1970; Zabawa, 1976; Moussavi-Harami, 1977) bore out the spatial relationship between the absence of Yelton salt and the presence of collapse structures in outcropping rocks. Suneson (2012) also recognized the relationship between Yelton salt karst and the distribution of collapsed blocks of Cretaceous strata in southwest Custer County, Oklahoma, just north of the Canute–Burns Flat area (discussed below).

The original extent of the Yelton salt in the Anadarko Basin is unknown. On both the north and south flanks of the synclinal basin, all the salt appears to have been dissolved (Figure 2). Along the axis of the basin, where the salt is thicker and more deeply buried, either all of the salt is still present or only some of the upper salt beds have been dissolved.

Most of the collapse structures are characterized by small- to moderate-sized areas (up to one or several hectares in size) where Permian strata dip at angles of 5–25 degrees, and strata in adjacent areas may dip in another direction, or may even appear to be undisturbed. The various blocks have subsided irregularly into the underlying cavities as salt was being dissolved. In addition, it is likely that some of the collapse structures are breccia pipes, which are cylindrical or irregular columns of broken rock (rubble) that are down-dropped into deep-seated salt cavities. It is likely that some of the Cretaceous collapse blocks are, in fact, the present-day outcrops of breccia pipes wherein Cretaceous strata were dropped some 50 m, or so, and are now juxtaposed with Permian strata.

Study Areas

Four areas of salt dissolution and collapse show the geographic range of salt karst and resultant collapse in the Anadarko Basin (Figure 1). Oklahoma examples are:

1) Beckham–Washita County line; 2) Canute–Burns Flat area, Washita County; and 3) northwest Beaver County. A fourth example is the Palo Duro Lake area, Hansford County, Texas.

Beckham–Washita County Line, Oklahoma

The Yelton salt is dissolved on the north and south sides of the Anadarko Basin in Beckham and Washita Counties, Oklahoma (Figure 2). The Yelton is the youngest salt unit in the basin, and it has been encountered at depths ranging from about 200 to nearly 400 m along the axis of the basin (Jordan and Vosburg, 1963). At shallower depths, on the flanks of the basin, the salt has been partly or totally dissolved, and overlying strata have collapsed into the salt-karst cavities.

The Yelton salt is about 66 m thick in the Shell LPG #1 Yelton well (the type well for the Yelton salt). It is as much as 87 m thick at the salt depocenter, about 8 km to the west of the Yelton well (Jordan and Vosburg, 1963), and it thins gradually to the north and south until it thins abruptly at its dissolution front (Figure 2). Cores and electric logs of the Yelton salt in the type well indicate that the unit is about 75–80% halite, and the remainder is red-brown and green-gray shale occurring as interbeds or as irregular masses within impure salt.

Collapse structures and disturbed bedding in outcropping strata of Beckham and Washita Counties have been well documented by field investigations (Smith, 1964; Richardson, 1970; Zabawa, 1976; Moussavi-Harami, 1977; Suneson, 2012). These chaotic-bedding features are outside of the area now underlain by Yelton salt, and correctly have been interpreted to result from salt dissolution and subsequent collapse.

Breccia pipes may well be present in this area (Figure 2), as there are many small chaotic collapse blocks of Cretaceous rocks exposed in the Canute area at the north end of the cross section (Richardson, 1970; Johnson and others, 2003). These Cretaceous blocks in the Canute area, and farther north, are commonly less than one hectare in size, but locally are up to 5–10 hectares.

Canute–Burns Flat Area, Washita County, Oklahoma

The Canute–Burns flat area, in northwest Washita County, is an excellent site to study dissolution of the Yelton salt and resultant collapse of overlying strata. Mapping of the surface geology by Richardson (1970), and later by Johnson and others (2003), shows the distribution of the collapsed blocks of Cretaceous strata, and this can be directly related to the present-day limits of the Yelton salt on the north side of the Anadarko Basin (Figure 3).

As shown above (Figure 2), the Yelton salt is dissolved on the north flank of the Anadarko Basin, and this causes subsidence and collapse of overlying strata. The Yelton is about 50–70 m thick in the southwest quarter of the Canute–Burns Flat study area, and it thins, by dissolution, both to the north and to the east (Figure 3). The salt unit is completely missing in the northern and far eastern parts of the area. Suneson (2012) describes an excellent exposure of collapsed Cretaceous rock in Custer County, just several kilometers north of the Canute–Burns Flat area.

By examining outcrops in the area, and comparing them with Yelton-salt distribution and thickness, it is possible



Figure 3. Thickness of Yelton salt showing saltdissolution area and collapse of overlying strata in the Canute—Burns Flat area of northwest Washita County, Oklahoma. Cretaceous collapse structures are mostly less than 1 hectare (2.5 acres).

to determine where the salt is present and where it is at least partly dissolved. This is accomplished by field mapping of areas where outcropping strata are disrupted or disturbed (that is, where they dip an angles of several degrees, or more), and where they appear to not be disrupted and disturbed, and assuming that the disruption is due to salt dissolution and collapse of all overlying strata. Unfortunately, much of the south half of this study area is mantled by several meters, or more, of Quaternary silt and sands (Richardson geologic map, 1970), and this conceals evidence of whether the bedrock is disrupted or not. Therefore, the precise limits of salt dissolution here cannot be determined by field work alone.

Gypsum beds (or anhydrite at depth) do underlie the Canute–Burns Flat area, but they are too thin and too deep for their dissolution to cause disruption of overlying Permian strata or collapse of Cretaceous rocks. Gypsum/ anhydrite beds in the Blaine Formation are 1–6 m thick, but they are at depths of 350–450 m. The only other unit with gypsum/anhydrite more than 1 m thick is in the Cloud Chief Formation: the basal gypsum is only about 3



Figure 4. Thickness of Flowerpot salt in northwest Beaver County, Oklahoma (from Jordan and Vosburg, 1963).

m thick and at depths of 100–150 m in the Canute–Burns Flat area—clearly too thin and too deep to contribute to this collapse.

Northwest Beaver County, Oklahoma

The northwest corner of Beaver County, Oklahoma, contains a dramatic example of salt dissolution and collapse. In most of Beaver County the Flowerpot salt typically is 100–150 m thick (Figure 4) (Jordan and Vosburg, 1963). However, in the northwest corner of the county the salt unit has been dissolved along a SW—NE trend, and overlying strata have collapsed and subsided about 100 m (Figure 5) (Jordan and Vosburg, 1963).

The structure at the base of the Blaine Formation (Figure 5) is definitely the result of dissolution of the underlying Flowerpot salt. Gypsum beds of the overlying Blaine Formation in the area are 1-4 m thick and are equally thick on both sides of the dissolution zone, so there is no evidence that dissolution of these gypsums plays a part in the subsidence and collapse.



Figure 5. Structure map on base of Blaine Formation in northwest Beaver County, Oklahoma (from Jordan and Vosburg, 1963).

Strata beneath the Flowerpot salt show no evidence of disturbance in this collapse zone. Structure mapping on the base of the much deeper Wellington evaporites (at a depth of about 1,000 m) shows that these strata dip gently, and uninterrupted, to the southeast at a rate of about 3–6 m/km across all of Beaver County (Jordan and Vosburg, 1963). Thus it is clear that the abrupt drop in elevation of the Blaine Formation in northwest Beaver County is due to the dissolution front, and not to any deep-seated structure.

This dissolution–collapse feature is a southern continuation of the Crooked Creek fault that has been well documented and described in Meade County, Kansas (Frye, 1942, 1950). Frye attributed the Crooked Creek fault in Kansas to dissolution of Permian salt and gypsum in the shallow subsurface, and it is now clear that it is principally dissolution of the Flowerpot salt in that area; gypsum (Blaine Formation) dissolution makes



Figure 6. Location maps showing area of salt dissolution and collapse in Hansford County, Texas. Cross section A—B shown in Figure 8.

little or no contribution to subsidence in Meade County or in Beaver County.

The timing for dissolution is uncertain. However, owing to the thick accumulation of the Miocene–Pliocene aged Ogallala Formation on the west side of the dissolution front, most of the dissolution apparently occurred prior to or during deposition of the Ogallala Formation (Irwin and Morton, 1969). Marine and Schoff (1962, Plate 1) also show great thicknesses of Ogallala and younger sediments on the west side of the dissolution front. Dissolution and collapse appear to be continuing: Irwin and Morton (1969) report that "recent sudden movement has occurred in Beaver County, Okla., and Hamilton County, Kans., where the land surface subsided several feet over a period of several months." Merriam and Mann (1957) report a number of recent and past sinks and sinkholes in southwest Kansas.



Figure 7. Resistivity and Spontaneous Potential log showing principal lithology in Palo Duro Lake area, Hansford County, Texas (modified from Johnson, 1989). Well is R. R. Fulton #3 Lasater; H&TC Survey, Block 45, sec. 72.

Palo Duro Lake Area, Hansford County, Texas

In eastern Hansford County, Texas, Late Cenozoic salt karst has resulted in subsidence and collapse of overlying strata in the vicinity of Palo Duro Lake (Figures 1, 6) (Johnson, 1989b). The Flowerpot salt is 0–107 m thick in the area (Figure 7), and at depths ranging from 180–335 m. However, most of the Flowerpot salt is dissolved beneath most of the study area (Figures 6, 8). Strata beneath the Flowerpot salt are essentially flat-lying and undisturbed (note the Cimarron anhydrite in Figure 8), whereas all the strata above the Flowerpot salt-karst zones are chaotic and are structurally low.

Elevation of the overlying Blaine Formation collapses and undulates, following closely the areas where dissolution occurs in the Flowerpot salt and even in the deeper Upper Cimarron salt.

Principal outcrops in the Palo Duro Lake area are sands and gravels of the Miocene–Pliocene age Ogallala Formation. Based upon well-log studies, the elevation of the Ogallala base is highly irregular, and the caprock, consisting of calcrete and silcrete, is disturbed and collapsed in two large subsidence basins in the area (one of which is shown in Figure 8). Inasmuch as the caprock is disturbed, salt dissolution and subsidence continued, at least locally, until after development of the caprock—after 3.5–2.4 My.

The dissolution front that crosses eastern Hansford County is a southwestward continuation of the northwest Beaver County feature (described above) and the Crooked Creek fault in Meade County, Kansas. There are, however, some patches or areas of Flowerpot salt that are partially or totally unaffected by dissolution farther west in both the Oklahoma and Texas Panhandles (Figure 1). Therefore, the structure of strata above the Flowerpot (the Blaine, Dog Creek,

Whitehorse, and Ogallala strata) can be quite variable: in places they will be horizontal and undisturbed, and elsewhere they will be at least somewhat chaotic and collapsed into underlying salt-karst zones.

Summary

Widespread Permian salts in the Anadarko Basin are locally dissolved and have resulted in subsidence and/or collapse of overlying strata in parts of western Oklahoma



Figure 8. Cross section showing salt dissolution and collapse of overlying strata at Palo Duro Lake in Hansford County, Texas (modified from Johnson, 1989). See Figure 6 for location.

and the Texas Panhandle. Chaotic structures, collapse features, and breccia pipes are present in outcropping Permian, Cretaceous, and Tertiary strata. These strata normally dip at an angle of less than one degree towards the axis of the Anadarko Basin, but may dip at angles of 5–25 degrees in various directions where an underlying salt unit is partly or totally dissolved.

It is clear that most (if not all) of these collapse features and chaotic dips result from dissolution of salt and collapse of overlying strata into deep-seated zones of salt karst. Whereas gypsum karst and resultant collapse had been proposed in many parts of the Anadarko Basin before, the gypsum beds are only 1–6 m thick and are more than 100 m deep in these study areas and cannot contribute to the collapse of overlying strata.

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EVAPORITE KARST IN THE PERMIAN BASIN REGION OF WEST TEXAS AND SOUTHEASTERN NEW MEXICO: THE HUMAN IMPACT

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Abstract

A significant minority of sinkholes in the greater Permian Basin region of west Texas and southeastern New Mexico are of human origin. These anthropogenic sinkholes are often associated with historic oil field activity, or with solution mining of Permian salt beds in the shallow subsurface. The well-known Wink Sinks in Winkler Co., Texas formed in 1980 and 2002 within the giant Hendrick oil field. The Wink Sinks were probably the result of subsurface dissolution of salt caused by fresh water leakage in improperly cased abandoned oil wells. In 2008 two catastrophic sinkhole events occurred a few months apart in northern Eddy Co., New Mexico, and a third formed a few months later in 2009 near Denver City, Texas. All three sinkholes were the result of solution mining operations for brine production from Upper Permian salt beds. The Eddy Co. sinkholes formed within the giant Empire oil and gas field, several kilometers from populated areas. In the aftermath of these events, another brine well operation was identified within the city limits of Carlsbad, New Mexico as having a similar geologic setting and pumping history. That well has been abandoned and geotechnical monitoring of the site has been continuous since 2008. Although there is no indication of imminent collapse, geophysical surveys have identified a substantial void in Permian salt beds beneath the brine well extending north and south beneath residential areas, a major highway intersection, a railroad, and an irrigation canal.

Introduction

Sinkholes and karst fissures formed in gypsum bedrock are common features of the lower Pecos region of west Texas and southeastern New Mexico. New sinkholes form almost annually, often associated with upward artesian flow of groundwater from karstic aquifers of regional extent that underlie evaporitic rocks at the surface (e.g., Martinez et al., 1998; Land, 2003a, 2006). A small but significant number of these sinkholes are of human origin, including the well-known Wink Sinks in Winkler Co., Texas (Figure 1). Wink Sink no. 1 formed in 1980 outside the small community of Wink, Texas, within the giant Hendrick oil field, destroying crude oil pipelines and oil field infrastructure. The sinkhole ultimately expanded to a diameter of 110 m, with a total estimated volume of 159,000 cubic meters. Wink Sink no. 1 appears to have been largely inactive for the past 30 years, but in May, 2002 a new sinkhole formed less than 2 km south of Wink Sink no. 1. Wink Sink no. 2 is significantly larger than its predecessor, with a maximum width of 238 m and an estimated total volume of 1.3 million cubic meters. Both sinkholes are assumed to have formed by dissolution of salt beds in the Upper Permian Salado Formation (Figures 2 and 3), in association with improperly-cased abandoned oil and water supply wells (Johnson et al., 2003). Powers (2003) reports that a sinkhole that formed near Jal, New Mexico (Figure 1), was probably the result of Salado dissolution related to an improperly-cased water well. These three sinkholes all overlie the Middle Permian Capitan Reef aquifer. In the case of the Wink sinks, Johnson et al. (2003) observe that hydraulic head of water in the Capitan Reef is locally above the elevation of the Salado Formation. Undersaturated water rising along a borehole by artesian pressure may have contributed to subsurface dissolution and collapse of the Wink sinkholes.

Sinkholes in the greater Permian Basin region have also resulted from solution mining of Permian salt beds in the shallow subsurface. The Borger sinkholes, in Hutchinson Co., Texas, are associated with solution mining operations conducted to extract brine from the Upper Permian Flowerpot salt beds. Surface subsidence was first observed in 1964, and sonar surveys revealed a subsurface cavity that had migrated to within 137 m of the surface. Within the next 14 years two sinkholes ~15 m deep and 50 m in diameter had formed above the cavern (Johnson et al., 2003).



Figure 1. Regional map of the lower Pecos region of southeastern New Mexico and adjoining areas of west Texas, showing locations of sinkholes discussed in text, and their position with respect to the Capitan Reef. WIPP = Waste Isolation Pilot Plant.



Figure 2. Diagramatic north-south stratigraphic section showing shelf-to-basin facies relationships in the Delaware Basin region. Line of section shown in Figure 1.

Geologic setting

The lower Pecos region includes the city of Carlsbad in Eddy Co., New Mexico (Figures 1 and 4). Evaporitic rocks, primarily gypsum, are widely distributed in the Carlsbad area both at the surface and in the subsurface (Bachman, 1984; Hill, 1996). Carlsbad is located on the Northwest Shelf of the Delaware Basin (Figures 1 and 2), a large hydrocarbon-producing sedimentary basin in west Texas and southeastern New Mexico (Land, 2003b). The uppermost part of the Delaware Basin section is comprised of ~1700 m of redbeds and evaporites of Upper Permian (Lopingian) age (Lucas, 2006a; 2006b). This section includes the Salado Formation (Figures 2 and 3), which in the subsurface of the Delaware Basin consists of ~710 m of bedded halite and argillaceous halite, with lesser amounts of anhydrite and polyhalite. Rare amounts of potassium salts (sylvite and langbeinite) occur in the McNutt Potash Zone near the center of the formation (Cheeseman, 1978). Clastic material makes up less than 4% of the Salado (Kelley, 1971). Potash ore is mined from the McNutt Potash Zone in underground mines a few kilometers east of Carlsbad. The formation is also the host rock for the Waste Isolation Pilot Plant (WIPP), a repository for transuranic radioactive waste in eastern Eddy County (Figures 1 and 3).

The Salado Formation thins to the north and west by erosion, halite dissolution, and onlap onto the Northwest Shelf of the basin. Because of the soluble nature of Salado rocks, the unit is very poorly exposed in an "outcrop belt" ~5 km east of the Pecos River valley (Figure 5). In that

area the Salado is represented by 10 to 30 m of insoluble residue consisting of reddish-brown siltstone, occasional gypsum, and greenish and reddish clay in chaotic outcrops. In most areas the Salado outcrop is covered by a few meters to tens of meters of pediment gravels and windblown sand (Kelley, 1971; McCraw and Land, 2008).



Figure 3. Upper Permian (Lopingian) stratigraphy in the northern Delaware Basin in the vicinity of the WIPP Site, southeastern New Mexico.



Figure 4. Map of study area in Eddy Co., New Mexico, showing locations of the Eddy County sinkholes. Southernmost filled circle shows the location of an abandoned brine well within city limits of Carlsbad.



Figure 5. West-east cross-section showing stratigraphic section penetrated by JWS sinkhole. Qpe = Quaternary pediment gravels and windblown sand.

Eddy Co. and Denver City sinkholes

Around 8:15 on the morning of July 16th, 2008, a driver for a local water service company was inspecting a brine well located on state trust land ~35 km northeast of Carlsbad. While on location the driver noticed a rumbling noise and quickly vacated the site. Minutes later, a large sinkhole abruptly formed, engulfing the brine well and associated structures (Figure 6). The well operator had been solution mining the Salado Formation by injecting fresh water and circulating it through the 86 m thick section of halite until the water reached saturation. The resulting brine was then sold as oil field drilling fluid. The brine well was being operated under permit from the New Mexico Oil Conservation Division (NMOCD).

This sinkhole, referred to as the JWS sinkhole from the initials of the well operator, was originally several tens of meters in diameter and filled with water to a depth of ~12 m below land surface. Large concentric fractures developed around the perimeter of the sink, threatening the integrity of County Road 217, 100 m to the south. By July 28, the walls of the sink had developed an angle of about 45° to within ~20 m below ground level, above which the sides of the sink were vertical, and the water originally present had subsided into the subsurface (Figure 7). There are no significant sources of groundwater at shallow depths in the immediate vicinity of the JWS sinkhole. Thus we assume the water was solution mining fluid that had been forced up the debris chimney in the initial stages of collapse, and was now stored in pore space in the resulting collapse breccia in the subsurface cavern. By this time the sinkhole had attained a diameter of ~111 m, based on

air photo interpretation, with an estimated depth of 45 m (Land and Aster, 2009).

Less than four months after collapse of the JWS sink, another brine well collapse occurred in northern Eddy Co. near the small community of Loco Hills (Figures 1 and 4), forming a sinkhole of similar dimensions. The Loco Hills sinkhole, which has subsequently been filled, was also the result of a brine well operation in the Salado Formation on state trust land. The well had been shut in three months earlier after it failed a mechanical integrity test as part of a statewide review of brine wells conducted in the aftermath of the JWS collapse. Then in July, 2009 another sinkhole abruptly formed near Denver City, Texas, ~115 km east of Loco Hills (Figure 1). The Denver City sinkhole was also the product of a solution mining operation.



Figure 6. JWS sinkhole on 7/19/2008, three days after initial catastrophic collapse. Water in sink is ~12 m below ground level. View to south, with County Road 217 in background.



Figure 7. JWS sinkhole on 7/28/2008, showing post-collapse draining and broadening. Note concentric fractures around margins of sink. Boulders in the sinkhole are approximately car-size.

Seismic record

On March 15, 2008, an EarthScope Transportable Array three-component broadband seismograph TA126 was installed ~13 km southeast of the JWS sinkhole (Figure 4). This transportable seismograph is a component of the National Science Foundation's EarthScope USArray continental seismic investigation program. About 6 hours before surface disruption at the site of the brine well, TA126 began recording high frequency (>5 Hz) seismic signals, with vertical ground motion velocity amplitudes of ~5 microns/s (Figure 8).

These seismic events probably reflect subsurface spalling during upward stoping of the cavern roof, with seismic energy resulting from the fall of material into the solution cavity (Land and Aster, 2009).

Solution mining

During solution mining operations a subsurface cavern is excavated. Most cavern excavation occurs at the top of the void space, since the injected fresh water floats on top of the denser brine. A cushion of crude oil or diesel fuel is sometimes injected into the void to protect the cavern roof and ensure that cavern excavation occurs outward rather than upward. This procedure was not applied in the brine well operations that produced the JWS and Loco Hills sinkholes. To prevent surface subsidence and collapse, brine well operators in New Mexico are required to conduct annual pressure tests and downhole sonar surveys to assess the size and proportions of the cavern being excavated. However, borehole problems prevented the operator from conducting these surveys. Apparently, the mechanical strength of the mudstone and gypsum in the overlying Rustler and Dewey Lake Formations was insufficient to prevent upward stoping of the cavern roof, causing an unanticipated catastrophic surface collapse (Figure 9).

I&W brine well

Formation of the Eddy Co. sinkholes in 2008 prompted NMOCD to review its regulations regarding brine well



Figure 8. Transportable array seismograph TA126-A 3-day high-pass (filtered above 5 Hz) record of vertical ground velocity (top), located 13.9 km southeast of the JWS sinkhole, showing more than 6 hours of apparent precursor ground motion associated with sinkhole formation. Estimated time of surface breaching (8:15am) indicated by vertical red line. Seismograph TA125 (lower plot), located 50.3 km from the site, showed no obvious candidate precursor signals.



Figure 9. Sequence of events associated with solution mining that led to development of the JWS sinkhole. Unnamed uppermost section consists of ~20 m of Quaternary sand, gravel, and calcrete.

operations in the southeastern New Mexico oil fields. During this review, the I&W brine well was identified within the city limits of Carlsbad (Figure 4) as having a similar geologic setting and pumping history. However, unlike the JWS and Loco Hills sinkholes, which are located in relatively remote areas in northern Eddy County, the I&W operation is sited in a more densely populated area within the city of Carlsbad near the BN&SF rail line and the intersection of two major highways (Figure 4). The Carlsbad Irrigation District (CID) South Canal is about 50 m south of the wellhead, and the immediate area also includes a feed store, truck stop, mobile home park, and Jehovah's Witness church. A catastrophic collapse in this area would inflict extensive damage to individual property and civic infrastructure, and possibly cause fatalities.

Following the collapse of the JWS Sinkhole, NMOCD ordered closure of the I&W brine well. The City of Carlsbad and Eddy County developed a monitoring, alarm, and emergency response system to prevent loss of life in the event that a catastrophic collapse should occur. Geotechnical monitoring of the site has been continuous since 2008, consisting of an array of tilt-meters and related devices that measure shifts, subsidence, and cracks in the immediate vicinity of the brine well.



Figure 10. South-north electrical resistivity profile across I&W brine well site. This line passes within 2 m of the I&W wellhead, thus crossing directly over the subsurface cavern excavated during solution mining operations. Low resistivity zones, shown in blue and purple, probably indicate brine-filled cavities or brine-saturated breccia zones. The low resistivity zones labelled A, B, C, and D correspond to potentially hazardous areas indicated in Figure 11.



Figure 11. Geophysical surveys conducted at I&W brine well facility from 2009 to 2011. Low resistivity zones A, B, C, D, and E defined by electrical resistivity survey are indicated by solid or dashed yellow lines; red filled area shows probable extent of the cavity excavated by the I&W brine well, as defined by resistivity surveys. Purple shading shows area where magnetotelluric surveys identified subsurface void thickness greater than 3 meters. White outline indicates area where a cavern signature was identified on 2D seismic reflection surveys. Inner white oval shows the area of greatest seismic disruption. Note that none of the seismic lines extended south of the CID South Canal.

NMOCD also initiated geophysical investigations, including electrical resistivity, magnetotelluric, and seismic reflection surveys, to determine the size, shape, and lateral extent of the cavity excavated by the I&W solution mining operation. A Technical Advisory Subcommittee has discussed the possibility of filling the cavity, but only in general terms, since a reliable selection of the best methods and materials to prevent a collapse is not possible until site characterization is complete.

Electrical resistivity surveys of the I&W brine well site, conducted by the National Cave and Karst Research Institute (NCKRI), indicate that the area is underlain by extensive low resistivity zones that represent either open cavities in the Rustler and Salado Formations caused by solution mining, and/or highly fractured and brine-saturated intervals within the Rustler Formation that may have been caused by sagging and collapse into underlying cavities (Land and Veni, 2011; 2012). These low resistivity zones extend to the north beneath the intersection of highways 285 and 62-180, and south beneath residential areas south of the CID South Canal. The data suggest that solution mining of the Salado Formation has caused significant upward stoping into overlying Rustler strata (Figure 10). This interpretation is consistent with results from seismic reflection surveys (Goodman et al., 2009) and the magnetotelluric survey (Woods, 2011) of the I&W site (Figure 11).

Conclusions

Sinkholes formed in evaporitic rocks are common features in the Permian Basin region of southeastern New Mexico and west Texas. A small but significant number of these features are of human origin, the product of improperly-cased water wells or abandoned oil wells, or solution mining of salt beds in the shallow subsurface.

Johnson (2002) observed that "most solution-mining collapses result from cavities formed 50-100 years ago, before modern-day engineering safeguards were developed. Proper, modern design has virtually eliminated this problem in new facilities." It would appear that developing engineering safeguards for solution mining is still an evolving science.

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EVAPORITE KARST AND HYDROGEOLOGY OF THE CASTILE FORMATION: CULBERSON COUNTY, TEXAS AND EDDY COUNTY, NEW MEXICO

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Abstract

Karst development in Permian Castile evaporites has resulted in complex speleogenetic evolution with multiple phases of diagenetic overprinting. More than 10,000 surficial features, primarily sinkholes, occur throughout Culberson County, Texas, and Eddy County, New Mexico, based on GIS-analyses where laminated Castile sulfates crop out. Cave development is largely the result of hypogene processes, where ascending fluids from the underlying Bell Canyon Formation migrate near vertically through the Castile Formation, creating caves up to 100 meters deep and over 500 meters long, which have been breached through a combination of collapse and surface denudation. Numerous small and laterally limited epigene features occur throughout the region, as well as the anomalously large Parks Ranch Cave System with more than 6.5 kilometers of cave development and multiple large, incised, sinkhole entrances. Hypogene caves exhibit varying degrees of epigenic overprinting as a result of surficial breaching.

Water resources in the Castile Formation are directly related to karst development with extremely heterogeneous flow networks. Most springs in the region discharge sulfate-rich waters, contain high levels of hydrogen sulfide, and support sulfate-reducing bacterial colonies. Isolated stream passages in northern Culberson County provide locally significant water resources that do not exhibit elevated hydrogen sulfide concentrations. Local water tables vary greatly over the region and few caves access base-level conditions. Upward migration of hydrocarbons complicates regional hydrology and diagenesis, resulting in extensive evaporite calcitization, which greatly modifies both fluid / rock interaction and permeability structures.

Introduction

The arid southwestern United States hosts unique evaporite-karst development, including extensive

caves and rapidly evolving landscapes, all of which are coupled to a complex and poorly understood hydrogeologic system. The Gypsum Plain is a large expanse of Permian-age evaporites that crop out in eastern New Mexico and far west Texas, with Castile strata outcrops limited to Eddy County, New Mexico, and Culberson County, Texas, along the western edge of the Delaware Basin (Figure 1). The region occurs within the northern portion of the Chihuahuan Desert with annual temperatures averaging 17.3 °C and an average low and high of 25.2 °C and 9.2 °C, respectively (Sares, 1984). Annual precipitation averages 267 mm, with greatest concentration occurring as high-intensity, short-duration events that promote rapid runoff associated with latesummer monsoonal storms.

Cave and karst development in far west Texas and southeastern New Mexico is extensive and widespread; however, most people envision the famous carbonate caves of the Guadalupe Mountains (e.g. Carlsbad Cavern, Lechuguilla Cave) when they think of this region, which have developed in Guadalupian reef (Capitan Formation) and near-backreef facies (Yates and Tansil formations) (Figure 2) (Hose and Pisarowicz, 2000). While often overlooked and generally less studied, evaporite karst in the region is more extensive and widespread. In the contemporaneous Guadalupian backreef facies, interbedded gypsum, carbonate, and clastic strata host numerous well-developed cave systems in the Artesia Group (Stafford and Nance, 2009). Post Guadalupian deposition, Ochoan basin-filling evaporites host extensive karst development in the Castile Formation, while strata overlying (Salado and Rustler formations) the Permian reef and basin-filling deposits exhibit similar karst development (Stafford and Nance, 2009).

Most research on evaporite karst associated with Permian deposition in the region has received little study, including geology (e.g. Forbes and Nance, 1997; Nance,



Figure 1. Castile Formation outcrop area showing relationship to major depositional features of the Delaware Basin and geomorphic features. Small inset shows relationship of Delaware Basin to the Orogrande Basin (OB), Val Verde Basin (VB) and Midland Basin (MB) (from Stafford et al., 2008c).

1993) and hydrology (e.g. Land 2006; Sares, 1984), with limited reporting associated with karst inventories conducted in conjunction with the Gypsum Karst Project (GYPKAP) of the National Speleological Society (e.g. Eaton, 1987; Belski, 1992; Lee, 1996). In the last decade, the Castile has been studied more significantly in an attempt to characterize its speleogenetic and diagenetic evolution of basin-filling evaporites (e.g. Stafford et al., 2008a, 2008b). Castile evaporites host a complex history that includes phases of hypogene and epigene cave development, high rates of landscape denudation, extensive evaporite calcitization, and a highly heterogeneous karst-aquifer system, thus creating a complex and evolving hydrogeologic system.

Study Area

The Castile Formation crops out over approximately 1800 km² in Eddy County, New Mexico, and Culberson County, Texas, extending from the Guadalupe Mountains in the north to the Apache Mountains in the south (Figure 1). The western portion of the Castile Formation exposure on the Gypsum Plain is formed by erosional truncation associated with the uplifted Delaware Mountains. To the east, the Castile Formation dips into the subsurface beneath younger strata where it reaches a maximum thickness of 480 meters (Kelley, 1971). Intrastratal speleogenesis and diagenetic alterations occur throughout the eastern portion of the Delaware Basin where Castile evaporites are exposed at the land surface (Stafford et al., 2008a). Permeable siliciclastics of the Bell Canyon and Cherry Canyon formations underlie the Castile Formation throughout the Delaware Basin; the carbonate reef facies of the Capitan Formation laterally limited Castile Formation basin-filling deposits (Figure 2) (Lee and Williams, 2000).

The Castile Formation was deposited in the Ochoan, subsequent to the Guadalupian deposition of the Capitan Reef, which is now exposed at the surface in the Guadalupe and Apache Mountains. Castile evaporites represent deep-water, restricted marine deposits which formed within the stratified, brine-filled Delaware Basin at the end of the Permian (Kirkland and Anderson, 1970; Kendall and Harwood, 1989). Castile strata consist of laminated calcite / gypsum (anhydrite) with interbedded halite. Sulfates are hydrated to gypsum near the surface and throughout the Gypsum Plain, but remain dehydrated in the deeper subsurface. Similarly, halite interbeds are



Figure 2. Simplified stratigraphic section of Permian strata in the Delaware Basin region (adapted from Scholle et al., 2004).

limited to more deeply buried portions of the Castile Formation where they have not been removed by intrastratal dissolution (Kelley, 1971). Calcite laminae were deposited during wetter / less-saline periods, while sulfate / halite laminae were deposited during dryer / more-saline periods. Commonly, original laminated fabrics have been diagenetically altered since deposition, creating irregularly laminated, massive, nodular, and selenitic textures (Hill, 1996).

Throughout the Castile Formation, evaporite calcitization is common and widespread. Stafford et al. (2008c) documented more than one thousand regions of calcitized evaporites exposed at the surface across the Gypsum Plain (Figure 3). These regions were subdivided into calcitization associated with vertical breccia pipes and calcitization associated with intrastratal dissolution of beds that created sheet-like horizons of brecciation. Kirkland and Evans (1976) attributed these calcitized evaporites to bacterial sulfate reduction; however, isotope analyses by Stafford et al. (2008c) showed that isotopic fractionation was insufficient to unequivocally differentiate the calcitization as being the result of bacterial sulfate reduction or thermal sulfate reduction. These extensive calcitized evaporites have formed along high-permeability zones where ascending hydrocarbon gases delivered from the underlying Bell Canyon and Cherry Canvon formations have migrated through Castile strata (Stafford et al, 2008c). Associated with most of the calcitized evaporites, intrastratal dissolution and recrystallization of microcrystalline sulfate into macrocrystalline sulfate (selenite) is common, as well as native sulfur, which is limited due to high rates of oxidation in near surface calcitized zones.

Surficial-Karst Development

Surficial-karst development where the Castile Formation crops out is widespread and diverse, ranging from large sinkholes to small karren developed on exposed bedrock (Stafford et al., 2008b). The Castile Formation has been heavily modified by surficial processes, with gypsic soil developed across the majority of the outcrop area (Figure 3); however, approximately eight percent (~140 km²) of the surface area is composed of exposed bedrock and less than one percent is calcitized evaporites. Alluvium associated with Quaternary gravels commonly occurs along incised drainages, while residual outcrops of the Rustler Formation occur as patchy remnants across the eastern and southern portion of the Gypsum Plain.



Figure 3. Castile Formation outcrop area geomorphic map, delineating zones of exposed bedrock, gypsite, calcitized evaporites, and karst features.

Solutional karren are well-developed on exposed bedrock, with typical varieties associated with the slope of the rock surface they are developed upon (Stafford et al., 2008b). Deeply incised rillenkarren form long solutional flutes on dipping rock surfaces, with the depth and length of rillenkarren increasing proportionally from moderately dipping surfaces to near vertical surfaces. Centimeter-scale spitzkarrren commonly occur at the apexes of dipping rock surfaces and converge through dendritic channels into rillenkarren. Kamenitzas form on near-horizontal rock surfaces, producing up to decimeterdeep solution pans that are floored with millimeter-thick algal crusts that hydrate during monsoonal storms. In addition to the normal karren forms, tumuli commonly occur throughout the Gypsum Plain, where secondary gypsum recrystallization has been laterally confined, resulting in a buckling of the local land surface over regions up to several meters. In regions where karren are less pronounced, cm-thick gypsic crusts develop on bedrock as a result of dissolution and reprecipitation of gypsum at the land surface (Stafford et al., 2008b).

Stafford et al. (2008a) identified 3,237 closed depressions across the Castile outcrop area using GIS analyses that coupled ten-meter digital elevation models with digital orthophoto quad analyses (Figure 4). However, Stafford et al. (2008a) predict that more than 10,000 individual closed depressions exist across the study area based on physical field mapping of fifty, one-square kilometer sites. From this study, sinkholes were classified based on length to width ratios, and it was determined that at least 55% of the closed depressions were collapse structures while the remaining 45% were a mix of purely incised arroyos and heavily modified collapse structures (Stafford et al., 2008a). Therefore, the majority of the sinkholes are the result of upward-stoping processes where surface denudation has enabled collapse features to breach the land surface and form surficial expressions of subsurface voids that may not have been originally coupled to surficial, meteoric processes.

The widespread occurrence of collapse sinks and well-developed incised, solutional sinks is directly coupled with the evolution of the Gypsum Plain geomorphology. Shaw et al. (2011) conducted a twoyear investigation of surface denudation across the region utilizing standard gypsum tablets. Their data show that surface denudation rates up to 60 cm/kyr occur within the Gypsum Plain (Figure 5); however, the majority of the region exhibits rates that average 30 cm/kyr, resulting in a high rate of landscape evolution. Most denudation occurs during the late summer /early fall monsoonal season, with rates generally increasing northward away from the Apache Mountains to the Guadalupe Mountains and Pecos River Valley, at the southern and northern margins of the outcrop area, respectively (Shaw et al., 2011). When compared with the distribution of karst development assessed through sinkhole delineation (Figure 4), a similar trend is observed; however, sinkhole distribution is highly localized and occurs more frequently towards the western portion of the Castile outcrop area where total Castile thickness is reduced on the updip side of strata.



Figure 4. Distribution of closed depressions across the Castile outcrop area derived from GIS analyses (modified from Stafford et al., 2008b).

Subsurface Karst Development

Cave development in the Castile Formation is diverse and widespread, but not uniform. The spatial distribution of caves mimics that of sink development delineated through GIS analyses (Figure 4), with clusters of intense cave development scattered amongst regions of poor cave development. Caves exhibit varying degrees of structural control, with many features being purely developed along fracture planes, while others show no distinct correlation to structural deformation (Stafford et al., 2008b). Cavernous porosity includes hypogene caves and intrastratal breccias, epigene caves, and hybrids that have resulted from epigenic overprinting of hypogene systems (Figure 6).



Figure 5. Average surface denudation for the Castile outcrop area based on standard tablet studies (modified from Shaw et al., 2011).

Most caves within the Castile outcrop area are small and laterally limited epigene features (Figures 6A & 6B), having formed as either local groundwater recharge features or shallow bypass features proximal to incised arroyos. Epigene caves exhibit scalloped walls, are developed along fracture planes, and can be associated with solutional sinkholes that cover several hectares and entrenched tens of meters. Small scallops on floors, ceilings, and walls indicate that high-velocity fluids routinely pass through these features, likely associated with extensive runoff during monsoonal storm events (Stafford et al., 2008b). Epigene cave apertures rapidly decrease away from entrance areas, generally becoming humanly impassable within a few tens of meters as a result of the rapid solution kinetics associated with calcium sulfate (Klimchouk, 2000). Zombie Cave (Figure 6A) and Dead East Cave (Figure 6B) are the largest purely epigene caves that have been documented within the Castile Formation, with survey lengths of 43 meters and 41 meters, respectively. Although exceptionally large for epigene caves in the Castile Formation, they exhibit typical characteristics, including: 1) narrow apertures developed along dominant fractures; 2) laterally limited, shallow features; and 3) solutional enlargement of secondary fractures proximal to the main conduit development. Most epigene features are developed in laminated, massive, and nodular facies; however, they occasionally develop in tabular (selenite) gypsum along crystal planes and in gypsite soils along zones of permeability contrast.

Hypogene-karst development is associated with extensive and deep cave systems within the Castile Formation, including complex, multi-storey cave systems and isolated solutional chambers (Stafford et al., 2008b). Hypogene caves exhibit classic morphometric features, including risers, cupolas, wallchannels, and ceiling channels, often connected in series that show the complete suite of morphological features created by ascending fluid flow in a mixed convection system (Klimchouk, 2007). Unlike epigene caves, hypogene features do not show rapid decreases in aperture width but instead exhibit zones of increasing pore volume beneath permeability boundary horizons. While hypogene caves do still exhibit passage correlation with fracture planes, they do not show speleogenetic dominance along preferential planes, but instead exhibit dissolution patterns indicative of noncompetitive flow (Stafford et al., 2008b). Dead Bunny Hole (Figure 6C) is developed along a combination of anticlinal structures and fracture planes with complex interconnected passages at multiple levels, while Bee Line Cave (Figure 6E) is largely a single solutional dome room in an ascending series of cupolas that have been overprinted by meteoric processes. Crystal Cave (Figure 6G), the deepest cave in the study area at 93 meters, is effectively a single ascending cupola series with interconnected ceiling and wall channels, in which the lowest portions of the cave descend below the current water table and are developed in selenite. Other hypogene caves in the study area (e.g. Black Dog Cave) exhibit inverse dendritic patterns where multiple




ascending fluid paths converge upwards through the subsurface; however, these patterns are not common in the study area.

While hypogene caves are the largest features in the study area, they are not the dominant cave type documented (Stafford et al., 2008b). This is likely a sampling bias because of the nature by which these caves form from ascending, transverse fluid flow. However, many of the hypogene features exhibit strong correlation with regions of evaporite calcitization and diagenetic recrystallization of original gypsum fabrics into tabular fabrics (Stafford et al., 2008c). Therefore, it is logical to assume that the higher-permeability zones created by hypogene karst development and evaporite calcitization were utilized by both ascending waters and hydrocarbons from the underlying Bell Canyon and Cherry Canyon Formations (Figure 7). The largest individual cave currently documented in the Castile Formation is Parks Ranch Cave with over 6.5 kilometers of surveyed passage (Figure 8). This anomaly does not fit the traditional models for either hypogene or epigene karst and likely represents a hybridization of the two genetic forms. Multiple, wellincised solutional sinkholes contribute meteoric runoff to the system which primarily discharges to Chosa Draw, a locally incised valley. Most passages exhibit well-developed scallops and generally the passages form a dendritic pattern; however, upper-level regions exist that are effectively scallop free and contain minor cupolas and poorly developed ceiling / wall channels (Stafford et al, 2008b). The current discharge point in Chosa Draw is a bisected cave passage and continues as

a stagnant water-filled conduit on the opposite side of the incised valley, indicating that this spring location is the result of downward cutting of the incised valley and conduit breaching. Parks Ranch Cave appears to contain minor hypogene components that have been connected and heavily overprinted by epigene processes, forming a complex, hydrologically active system.

Water Resources

Water resources in the Castile outcrop area are scarce and limited to occasional springs, seeps, and caves that breech conduits. Most springs and seeps in the study area exhibit high total dissolved solids, primarily sulfate, as a result of the rapid saturation of waters passing through gypsum facies (Stafford et al., 2008b). However, some springs have low enough total dissolved solids to support diverse ecological systems, including several species of arthropods and healthy, riparian zones at discharge points. All of these features, both sulfaterich and relatively fresh water resources, are utilized by local flora and fauna and are heavily relied upon by local ranchers for livestock.

Many of the springs provide perennial discharge and degas significant quantities of hydrogen sulfide; these springs host large colonies of white filamentous bacteria that are most likely sulfate-reducing forms. These features are likely associated with ascending fluids containing elevated hydrocarbons that provide source material for current evaporite calcitization in the subsurface and represent upward leakage of active hypogene processes to the land surface (Stafford et al., 2008b). China Mine,



Figure 7. Simplified paleohydrology diagram associated with evaporite calcitization and upward migration of hypogene fluids (adapted from Lee and Williams, 2000). White arrows show migration paths of meteoric waters; blue areas show migration paths of upward migrating, hydrocarbon-rich fluids.



Figure 8. Simplified plan view map of Parks Ranch Cave with entrances labeled ("e"). Note that the easternmost entrance was formed by conduit truncation as Chosa Draw entrenched, while the western entrances are associated with sinkholes (from Stafford et al., 2008a).

an early 20th century sulfur mine in northern Culberson County, currently degasses significant amounts of hydrogen sulfide and shows evaporite calcitization and secondary sulfur deposition but does not exhibit spring discharge (Stafford et al., 2008c); however, it is likely that it is a nonaqueous version of the smaller hydrogen sulfide springs. Similarly, Cave Well Cenote is a collapse structure approximately 15 meters in diameter that drops approximately 10 meters to water which forms a lake 15 to 20 meters deep (Figure 6F). The feature degasses extensive hydrogen sulfide and filamentous bacteria occur throughout the lake. While this feature does not discharge to the surface as a spring, it does provide a window into the local water table, while a nearby water well descends over 50 meters to the local water table.

Several caves in the area are vadose conduits, where relatively unsaturated waters flow through the shallow subsurface. Brantley Stream Cave (Figure 6D) contains over 100 meters of cave passage with an active stream that sumps in regions and discharges to the Delaware River, a perennial stream in northern Culberson County. Similarly, a series of collapse sinkholes intersect a separate conduit system in Sinkhole Flat approximately 20 kilometers southeast of Brantley Stream Cave on the opposite side of the Delaware River. These collapse sinks provide windows into a relatively freshwater conduit system approximately 10 meters beneath the land surface with no obvious surface connections; however, the stream exhibits low total dissolved solids. In the southern portion of the study area, Crystal Cave descends to a depth of 93 meters where the passage becomes sumped (Figure 6G), but does not exhibit

indications of high hydrogen sulfide and is relatively fresh. These features along with other isolated caves across the study area provide windows into the current hydrologic system, which are distinctively different than those water resources with active filamentous microbial communities.

Water resources across the Gypsum Plain provide a glimpse into the extremely heterogeneous hydrogeologic system. Fluid chemistry varies rapidly over distances of several kilometers, with water tables that appear to fluctuate extensively across the region. The hydrogeologic system couples components of shallow meteoric flow driven by gravity with ascending fluids that often exhibit a minor thermal component, high total dissolved solids, and host complex bacterial colonies. The complexity of the hydrologic system does not fit simple models for groundwater flow. More research is needed to delineate fluid flow paths across the region, which will need to couple mixed fluid flow components with aquifer compartmentalization.

Conclusions

The Castile Formation crops out in the western Delaware Basin in Eddy County, New Mexico, and Culberson County, Texas, and hosts extensive karst development. Surface denudation is rapidly modifying the landscape at rates averaging 30 cm/kyr, which has resulted in the surficial breaching of numerous caves throughout the region. More than ten thousand individual sinkholes have been predicted for the region based on GIS analyses, with over three thousand documented. Sinkholes provide windows into the complex speleogenetic evolution of the region, where hypogene caves form deep and complex systems that are being actively overprinted by epigene processes. Associated diagenetic alteration of the Castile sulfates has produced widespread regions of evaporite calcitization in association with ascending hydrocarbons from underlying clastic strata. The Castile Formation records the evolving hydrogeologic history of the Delaware Basin as multiple phases of hypogene and epigene fluids have modified the strata, creating a system that is continuing to be overprinted by current and active processes.

Initial Castile Formation studies indicate a complex hydrogeologic system that couples ascending transverse flow with descending meteoric waters. Mixing fluid chemistries have resulted in an extremely heterogeneous system in which perched water tables and a high degree of aquifer partitioning are prevalent in aquifer system. Future studies should focus on delineating this compartmentalization and unraveling geochemical signatures of the fluid system. Coupling of an active hydrologic system with consistent perennial flow and intense recharge / runoff during monsoonal seasons creates a continuously evolving system that can pose significant geohazards as rapid surface denudation continues to breach the system.

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GYPSUM KARST CAUSES RELOCATION OF PROPOSED CEDAR RIDGE DAM, THROCKMORTON COUNTY, TEXAS

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Abstract

Cedar Ridge Dam and Reservoir will be built to supply water for the city of Abilene, Texas. The original damsite (CR) was to be located on Clear Fork of Brazos River in Throckmorton County, but initial coring of the damsite encountered unsuspected gypsum beds in the Permianage Jagger Bend/Valera Formation. Gypsum is a highly soluble rock that typically contains karst features, and its presence in a dam foundation or impoundment area could allow water to escape from the reservoir. A decision was made to look at potential sites farther upstream (to the southwest), where west-dipping gypsum beds would be deeper underground and karst problems would be minimized or eliminated.

The first phase of the relocation was a comprehensive field study of Clear Fork Valley, upstream of the original damsite, to identify gypsum outcrops; gypsum was exposed at only one location, just above damsite CR. The second phase of the study was examination of nearly 100 petroleum-test geophysical logs to identify, correlate, and map the subsurface gypsum and associated rock layers upstream of the original damsite. The gypsiferous sequence is 30-45 m thick, and consists of 8 gypsum beds, mostly 1-3 m thick, interbedded with redbrown and gray shale units 1-10 m thick. Gypsum beds comprise 25–30% of the gypsiferous sequence. Gypsum beds dip uniformly to the west at about 7 m/km (about 0.4 degrees), and thus the uppermost gypsum is at least 23 m beneath the newly proposed damsite (A), about 8 km to the southwest.

Subsequent coring and other studies of the new damsite A confirm that gypsum beds are 23 m beneath the newly proposed dam. There is no evidence of solution channels or other karst features beneath this site, and thus there is little likelihood of water loss from the reservoir at the new site due to gypsum karst.

Introduction

This study examines aspects of the subsurface geology of an area along the Clear Fork of Brazos River (Clear Fork) in parts of Throckmorton, Haskell, Shackelford, and Jones Counties, Texas (Figure 1). The study area extends from the town of Lueders in the southwest to Paint Creek in the northeast. It includes the originally proposed Cedar Ridge Reservoir damsite (CR) and the newly proposed damsite (site A), located about 8 km farther upstream (to the southwest). The study focuses on the distribution, thickness, and structure of a series of gypsum beds present in the Permian-age Jagger Bend/Valera Formation, which dips gently to the west at a rate of about 7 m/km.



Figure 1. Location map showing originally proposed Cedar Ridge Reservoir damsite (CR), and site of the newly proposed dam (A) and reservoir.

The current study was prompted by the unexpected discovery of significant beds of karstic gypsum at the originally proposed damsite during a preliminary investigation in the summer of 2008. Because gypsum was not known to crop out in the area (it is eroded, dissolved, or soil-covered), previous geologic maps and studies of the area made no mention of gypsum occurrences in the Jagger Bend/Valera Formation. So, not only was it a surprise to discover karstic gypsum in preliminary cores at the original damsite, but also a blowout of natural gas was encountered at a depth of 20 m beneath the proposed dam alignment at CR.

Gypsum is a highly soluble rock. Generally, it is susceptible to partial or total dissolution by ground water, and may develop karst features such as caves, sinkholes, and underground water courses (Johnson 2003a, 2008a). Gypsum beds underlie all parts of the study area: they crop out at one small site about 1 km upstream of CR, and should also be present along the river for several km farther upstream in the Clear Fork Valley (however, they do not crop out). Due to the potential for gypsum karst along this portion of the river, the distribution and depth of the various gypsum beds are important factors to consider when choosing the final damsite along Clear Fork.

Gypsum karst is an important consideration in dam location and construction because it has had an adverse impact on holding water behind a dam at several sites in the United States. Dams built upon gypsum karst generally have difficulty in retaining water, and can even result in collapse and failure of the dam (Johnson, 2008a, 2008b). If gypsum karst is located within the proposed impoundment area of a reservoir, water can penetrate the karst features and may escape from the reservoir. Several articles have been published on properties of dam foundations built upon gypsum deposits (James and Lupton, 1978; Chen and Wu, 1983; Milanović, 2000).

Several examples of gypsum-karst problems and dams in the United States are: Quail Creek Dike (Utah), Upper Mangum Dam (Oklahoma), Anchor Dam (Wyoming), and Horsetooth and Carter Lake Dams (Colorado) (Johnson, 2008b). Quail Creek Dike failed in 1989 due, in part, to flow of water through an undetected gypsum-karst unit beneath an earth-fill embankment (James and others, 1989; O'Neill and Gourley, 1991; Payton and Hansen, 2003). The long-studied Upper Mangum Dam was abandoned before construction, because of extensive gypsum karst in the abutments and impoundment area (Johnson, 2003b). Anchor Dam, built in 1960, has significant drainage of water from the reservoir because of earth fissures, sinkholes, and gypsum karst that underlie the impoundment area (Jarvis, 2003). Horsetooth and Carter Lake Reservoirs, built upon gypsum-bearing strata in the 1940s, experienced development of sinkholes and seepage-loss of water in the 1980s and 1990s (Pearson, 2002).

Methods of Study

Determining the subsurface distribution, thickness, and structure of gypsum beds in the study area required examining the electric logs (also known as "geophysical logs") of nearly 100 oil and gas tests drilled within a 13 x 30-km area that extends about 6 km on each side of Clear Fork. Recognition of gypsum beds and associated rock types on electric logs is well established (Alger and Crain, 1966), and the senior author has conducted many studies using various types of well logs to identify, correlate, and map gypsum beds in the subsurface some of these studies are available in public documents (Johnson, 1967, 1981, 1985, 1989a, 1989b, 1993), and many others are contained within consulting reports.

On each well log examined in the study area, individual gypsum beds (and interbedded shale units) that are at least 0.5 m thick can be identified readily (Figures 2, 3, 4). Recognition and identification of gypsum beds on the electric logs is confirmed by comparison and correlation with continuous cores that were drilled near several of the oil wells. Figure 2 shows Core B-3, drilled on May 21, 2008, at the original Cedar Ridge damsite. The core contains gypsum beds, 0.3-2 m thick, that are readily correlated with gypsum beds interpreted to be present on electric logs for two wells (#69 and #66) drilled 100 m and 3 km, respectively, away from the core. There is almost a bed-for-bed correlation of the gypsums from Core B-3 with those in Well 69, and also a good correlation with those in Well 66, located 3 km away. Well 66 contains several thin gypsum beds at the top of the sequence that are missing in Core B-3.

Farther to the southwest, in the vicinity of newly proposed damsite A, gypsum beds in Core B–5 (drilled March 31, 2009) are readily correlated with those in the electric log of Well 2–5, located about 900 m away (Fig. 3). The gypsum beds, 0.3–3 m thick, are herein informally named A through H (in ascending order): these names



Figure 2. Gypsum beds in Core B–3, drilled at the original Cedar Ridge damsite (CR), are correlated with electric logs of nearby oil wells.

are shown on the left side of Core B–5 (Figure 3). Also showing up very clearly is another rock unit that is herein referred to informally as the "Upper Shale": this shale is 6–10 m thick, and immediately overlies gypsum H. In Cores B–3 and B–5, the shales interbedded with gypsum are generally 1–10 m thick.

Results of Study

With recognition of gypsum and shale beds on these electric logs (Figures 2, 3), confirmed through examination of nearby cores, it is then possible to confidently identify and correlate individual gypsum and shale units of the Jagger Bend/Valera Formation on other electric logs throughout the study area (Figure 4). Figure 4 is a structural cross section showing that the gypsum beds dip to the west, and therefore are deeper below the land surface and below Clear Fork to the west. It also shows that some of the gypsum beds present in the west are thinner to the east, and some of them disappear and even grade laterally into shale to the east.

The entire gypsum sequence is about 45 m thick near proposed damsite A, and is about 30 m thick in the vicinity of the original damsite CR. Gypsum beds comprise about 30% of the total thickness of



Figure 3. Gypsum beds in Core B–5, drilled near newly proposed damsite A, are correlated with electric log of a nearby oil well.



Figure 4. Structural cross section showing gypsum beds dipping down to the west. Gypsum beds thin and grade laterally into shale to the east.

the gypsum sequence near damsite A, and about 25% of the total thickness near CR.

Upon establishing the recognition of gypsum and shale units on electric logs, all 100 of the well logs within a larger study area were examined and the gypsum and shale units were identified and correlated. The depth to the top of the uppermost gypsum in the sequence (gypsum H, in most wells), was identified and plotted on a map (Figure 5). In some areas, mainly in the western part of the study area, additional gypsum beds are present above gypsum H and also below gypsum A. These additional beds are considered part of the Jagger Bend/Valera gypsum sequence in those areas. Similarly, towards the east, the upper and lower gypsum beds disappear and grade laterally into shale, and the Jagger Bend/ Valera gypsum sequence becomes thinner.

Figure 5 is a structure-contour map on gypsum beds at the top of the gypsum sequence in the Jagger Bend/ Valera Formation. It shows that the gypsum units dip fairly uniformly towards the west, at about 7 m/km.



Figure 5. Structure-contour map on top of youngest gypsum bed in Jagger Bend/Valera Formation. Elevations at each well are in feet, but contour interval is 6 m (±20 feet).

Local irregularities do exist, where the dip is slightly higher or lower, and the direction of dip varies slightly. For example, the dip is about 6 m/km in the vicinity of proposed damsite A, near the common corner of Throckmorton, Haskell, and Shackelford Counties.

Figure 5 is very significant because it shows the elevation (above sea level) of the top of the highest gypsum bed throughout the area. By comparing this map (the elevation of the highest gypsum) with topographic maps, it is possible to determine how deep the gypsum is below the land surface, and also whether gypsum beds should be exposed in the valley walls of Clear Fork. The uppermost gypsum beds are exposed, or should be exposed, in the valley of Clear Fork at and near the originally proposed Cedar Ridge Reservoir damsite (CR). Gypsum does crop out at one location near CR, but at other places where it should crop out the gypsum is either eroded, dissolved, or is covered by alluvium, colluvium, or soil.

If a dam is constructed upon gypsum, or if lake water is impounded too closely above gypsum in Clear Fork Valley, it could be detrimental to dam integrity. Potential karst development in the gypsum could provide pathways for impounded water to escape from the reservoir and be discharged downstream of the dam. Also, if such a pathway is established, the gypsum would undoubtedly be further dissolved, and the pathway would be enlarged. Therefore, it is important to know where gypsum does, or should, crop out in Clear Fork Valley. The elevation of the top of the gypsum sequence is about 17 m above stream level of Clear Fork at the original Cedar Ridge damsite, and thus the upper part of the gypsum sequence is, or should be, exposed in the valley walls (Figure 6). The top of the gypsum is then at successively lower heights above stream level in the valley upstream from CR because of: a) westward dip of the gypsum sequence (Figures 4, 5, 6); and b) the rise of stream-level elevation upstream from CR (Figure 6). The uppermost gypsum dips beneath stream level in the vicinity of borehole SB–4. Therefore, gypsum is present, or should be present (based on electric-log interpretation), in all parts of Clear Fork Valley from CR up to the vicinity of borehole SB–4 (Figures 5, 6).

The top-most gypsum (gypsum H) is about 23 m below stream level at proposed dam A. Here the gypsum beds are believed to be deep enough below the proposed reservoir to not pose a "gypsum-karst" problem. In addition, the presence of the 6- to 10-m-thick "Upper Shale" adds a low-permeability barrier between the gypsum beds (below) and the impounded reservoir water (above).

Another result of this subsurface study is recognition that a large number of oil and gas wells have been drilled along and near Clear Fork in the study area. These wells are beneficial for the current study, because they provide many electric logs that can be used to evaluate



Figure 6. Schematic cross section showing west dip of gypsum beds beneath Clear Fork of Brazos River and damsites CR and A. Top of gypsum sequence is above stream level at CR, and is about 23 m below stream level at damsite A.

the thickness, depth, and distribution of gypsum beds. However, this also means that there are a large number of wells in the impoundment area of the proposed reservoir that could impact the reservoir and its water quality. These boreholes are potential pathways for oil, gas, or associated salt-water brines to seep to the surface and mix with reservoir water. They also are potential pathways for reservoir water to flow down into the gypsum beds. Producing oil and gas wells in or adjacent to the impoundment must be properly plugged and sealed; and even dry or abandoned wells within the impoundment area must be found, to ensure that they have been properly plugged and sealed.

Summary

Gypsum is a highly soluble rock that typically contains cavities, sinkholes, and caves ("karst" features), and its presence in a dam foundation or in an impoundment area could allow water to escape from the reservoir. The presence of gypsum at the original Cedar Ridge damsite (CR) on Clear Fork of Brazos River was confirmed in core holes, and a decision was made to look at potential sites farther upstream where any gypsum-karst problem would be minimized or eliminated.

The current study focused on examination of nearly 100 oil- and gas-well electric logs to identify, correlate, and map the gypsum and associated rock layers of the Jagger Bend/Valera Formation within a 13 x 30-km area encompassing Clear Fork. Gypsum beds can be identified readily on the logs, and this is affirmed by comparing several cores (B–3 and B–5) with nearby electric logs (Figures 2, 3). Gypsum beds dip fairly uniformly to the west at about 7 m/km, and at 6 m/ km in the vicinity of prospective damsite A (Figures 4, 5). Gypsum beds in the study area thin to the east; they grade laterally into shale and pinch out in that direction.

Gypsum beds crop out, or should be exposed, in the Clear Fork Valley upstream from the original Cedar Ridge damsite, all the way to the vicinity of borehole SB-4 (Figures 5, 6). The presence of gypsum beds in this portion of the valley means that there may be karst pathways whereby impounded water could escape a reservoir built downstream of SB-4. Therefore, the best location for a dam on Clear Fork would be at a site located some distance upstream from SB-4, at a site where a sufficient thickness of the "Upper Shale" and other strata are present to separate reservoir water from the gypsum sequence.

At the newly proposed damsite (A), the Clear Fork streambed is 23 m above the shallowest gypsum bed, and the "Upper Shale," a low-permeability barrier just above the gypsum sequence, is 6–10 m thick. The latest core drilling at this site does not indicate the presence of any karst features in any of the gypsum beds. Therefore, this site appears to be favorable and warrants further investigation.

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THE ROLE OF SULFATE-RICH SPRINGS AND GROUNDWATER IN THE FORMATION OF SINKHOLES OVER GYPSUM IN EASTERN ENGLAND

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Abstract

Heavily karstified gypsum and dolomite aquifers occur in the Permian (Zechstein Group) of Eastern England. Here rapid active gypsum dissolution causes subsidence and abundant sinkholes affect an approximately 140-km by 3-km area from Darlington, through Ripon to Doncaster. The topography and easterly dip of the strata feed artesian water through the dolomite up into the overlying gypsum sequences. The shallow-circulating groundwater emerges as sulfate-rich springs with temperatures between 9-12 °C, many emanating from sinkholes that steam and do not freeze in the winter (such as Hell Kettles, Darlington). Water also circulates from the east through the overlying Triassic sandstone aquifer. Calcareous tufa deposits and tufa-cemented gravels also attest to the passage and escape of this groundwater.

The sizes of the sinkholes, their depth and that of the associated breccia pipes are controlled by the thickness of gypsum that can dissolve and by the bulking factors associated with the collapsed rocks. The presence of sulfate-rich water affects the local potability of the supply. Groundwater abstraction locally aggravates the subsidence problems, both by active dissolution and drawdown. Furthermore, the gypsum and dolomite karstification has local implications for the installation of ground-source heat pumps. The sulfate-rich springs show where active subsidence is expected; their presence along with records of subsidence can inform planning and development of areas requiring mitigation measures.

Introduction

Sulfate-rich springs are associated with the Permian Zechstein Group gypsum sequences of the Edlington and Roxby Formations in northeast England (Figure 1).

These gypsiferous sequences are both underlain by dolomite or dolomitic limestone aquifers (Figure 2).



Figure 1. Map of study area showing locations of main groups of sulfate-rich springs.

The Edlington Formation containing up to 40 m of gypsum is underlain by the Cadeby Formation aquifer and overlain by the Brotherton Formation aquifer. This in turn is overlain by the Roxby Formation with another 10 m or so of gypsum that itself passes up into the major aquifer of the Sherwood Sandstone Group (Figure 3). The Permian sequence dips gently eastwards with a dip of a degree or so. It presents a wide dip slope of Cadeby Formation dolomite which acts as a rain-catchment area that collects water and channels it down dip to the east where it rises up in the lower ground through the gypsiferous sequence (Figure 2 and Cooper, 1986, 1988, 1998). The local rainfall averages around 594mm a year in the south and 648 mm in the north (for 10 - 38year averages over 6 sites; Leeming, Topcliffe, Church Fenton, Linton on Ouse and Dishforth); the average temperature for Leeming over 38 years was 9.2°C with a minimum average of 4.7°C and a maximum average of 13.1°C (Tutiempo 2013). It typically varies from 1°C to 20°C and is rarely below -4°C or above 20°C (Weatherspark, 2013).

Numerous sulfate-rich springs occur at the foot of the dip slope and across the outcrop of the overlying strata (Figure 2). Many springs emerge under artesian pressure, some from within sinkholes that do not freeze in the winter due to the groundwater being at a temperature of 912°C.

The outcrop of these strata, where gypsum is present in the sequence and sulfate-rich springs occur, covers an area about 140 km long and 3 km wide extending from near Doncaster in the south through Askern, Boston Spa (Thorpe Arch), Knaresborough, Ripon, and east of Bedale to Darlington and the coast at Hartlepool (Cooper, 1986, 1998) (Figure 1). The area is prone to subsidence and sinkhole formation caused by the dissolution of the gypsum and the evolution of gypsum cave systems beneath the area. Some places are more susceptible than others and these tend to be where partly in-filled or buried valleys cut through the sequence allowing enhanced water flow.

In the north near Darlington, sulfate-rich groundwater escapes where the Tees Valley cuts the Permian sequence (Lamont-Black et al., 2002, 2005). The water forms the Spa springs at Croft and Hell Kettles a group of 3 sinkholes, one of which collapsed in the 12th century. Farther south, sulfurous water is recorded at Snape Mires near Bedale. Sulfate-rich groundwater is noted from here south to Ripon where the Permian sequence is cut through by the Ure Valley. Here tufa-depositing springs occur, forming tufa-cemented gravels (Cooper, 1986) and similar water emanates from the petrifying spring of the Dropping Well near Knaresborough. In the south of the area, sulfate-rich water is noted around Brotherton and subsidence ponds at Askern. The ponds at Askern, Hall Garth Ponds (Nunwick near Ripon) and Hell Kettles (near Darlington) all have or had artesian water emanating from them at a temperature sufficient to prevent them freezing easily in the winter.

The groundwater flow and active gypsum karstification leads to the formation of sinkholes that can be up to 20 m or more across and up to 20 m deep (Cooper, 1986, 1989,



Figure 2. Generalised cross-section through the easterly dipping Permian sequence showing water flow through the Permian dolomites and limestones into the Permian gypsum and then to the surface. The geological sequence is shown in Figure 3.



Figure 3. Vertical section through the Permian Zechstein Group se quence in northern England; for lithological legend see Figure 2.

1998). Planning for these problems and developing such areas requires special engineering mitigation measures (Paukstys et al., 1999; Cooper and Saunders, 2002; Cooper, 2008a, 2008b; Gutiérrez et al., 2008).

Sulfate-rich springs Historical records of sulfate-rich springs

The historical records of springs and wells give us an insight into the locations and approximate characters of many mineral waters. Waters high in sulfur/sulfate were particularly sought for their medicinal purposes with long lists of cures attributed to them. We used these early records to help us locate sulfate-rich springs that we then sampled using modern techniques.

As early as the mid-17th century, doctors were investigating the nature of the mineral waters that they prescribed as cures for many ailments. Burrell (1896) records that examination by Dr French in 1654 of the Dropping Well water at Knaresborough found a pint weighed 10 grains more than a pint of common water. This equates to approximately 1140 mg/l of dissolved solids. In the 18th century Thomas Short described several "sulphur-waters" including the petrifying water of the Dropping Well at Knaresborough and the waters of "Croft Spaw" near Darlington and "Askern Spaw", both of which he noted as having a white sediment deposit (Short, 1734). From the 18th century onwards, the mineral springs of the country were more extensively documented for their medicinal properties and the ailments they were thought to cure. Consequently, many medicinal scripts were written on the efficacy of the waters. Dr Robert Willan (1757-1812: Booth, 1999) was one such practioner who published on the sulphur waters of Croft, near Darlington and at Harrogate (Willan, 1782, 1786). Winch (1817) quoting analyses done by Peacock in 1805 showed the Croft water to be high in calcium sulfate.

The waters of Askern north of Doncaster were similarly described for their medicinal benefits by Brewerton (1818) and Lankester (1842) both with analyses presented in grains per gallon showing the waters to be high in dissolved calcium sulfate. Edwin Lee (1854) wrote an extensive treatise on "The Watering Places of England - considered with reference to their Medicinal Topography" with mention of the springs at Dinsdale (near Neasham) and Croft near Darlington plus the springs at Askern; his work also presents analyses of the waters. Some of these very early analyses give what we would now consider very strange combinations of elements, but in general they show high concentrations of calcium sulfate and the weights of dry residue of the analyses can be considered fairly accurate. In the late 19th century, studies of the mineral waters became based more on their geological origins with papers by Bothamley (1894) on the mineral waters of Askern and by Burrell (1896) on the water of the Dropping Well at Knaresborough.

We have used these historical records both to find the springs, but also to compare with our modern analyses. In some cases springs have disappeared due to groundwater abstraction or piping away in culverts, and these old references are the only records.

Because the sulfate-rich water is groundwater, commonly under artesian pressure, it can be warmer than surface temperatures and many of the ponds associated with the springs were noted for not freezing in the winter. This characteristic is also enhanced by the amount of dissolved chemicals in the water. The Mather Pit at Askern (Lankester, 1842), Hell Kettles at Croft, and Hall Garth Ponds near Ripon (AHC personal observation) all steamed in cold weather. The sulfate-and carbonate rich water is also favorable to the deposition of calcareous tufa, the best example of which is the Dropping Well tufa screen at Knaresborough (Burrell, 1896; Cooper and Burgess, 1993). Tufa-cemented deposits are widespread and associated with the sulfate-rich spring activity with cemented gravels at Ripon (Thompson et al., 1996; Cooper, 1998).

Modern sampling and analyses of sulfate-rich springs

Described from north to south, the main sulfate-rich springs are shown on Figure 1 and detailed in Table 1. The analyses were undertaken by three of the authors for their MSc studies (Miller, 2006; Greenwood, 2008; Brown, 2010).

Hell Kettles

At Hell Kettles there are three sinkholes, two combined into Double Kettle and one by itself a little to the south (Figure 4). Artesian sulfate-rich water overflows from the kettles, which are a Site of Special Scientific Interest for their uncommon flora. The highest concentrations of sulfate occur in the southern sinkhole, reaching 1225 mg/l (Table 1). The geological setting here is similar to that shown in Figure 2, being in the alluvial tract of the River Tees where it cuts down through the Permian sequence. Oxen le Fields Farm borehole is located about 400 m northeast of the kettles and yielded water less rich in sulfate than that seen at Hell Kettles.

Croft Sweet Well and Spa

Situated about 1.5 km south of Hell Kettles, the spring is near the base of the Cadeby Formation dip slope and formerly fed the spa hotel at Croft. The water is rich in sulfate (867 mg/l) and fairly high in carbonate.



Figure 4. Hell Kettles near Croft, Darlington. Double Kettle on left, Croft Kettle on right; north is to the left and the field is 190m wide; oblique view on digital terrane model. Air Photography copyright UKP/Getmapping reproduced under licence No UKP2006/01.

Neasham Low Springs

Located to the east of Hell Kettles, these springs emanate from the Triassic Sherwood Sandstone Group and negligible amounts of sulfate are present.

Snape, Snape Mires, and Gruntland springs near Bedale Snape Mires is a large flat area of glacial-lake deposits with abundant subsidence features (Cooper, 1986; Powell et al., 1992). The area is a bedrock depression caused by subsidence due to gypsum dissolution. It is fed by water under artesian pressure from the Cadeby Formation dip slope to the west (pale blue on Figure 2) where at the dip slope base the prolific and sulfatepoor Mill House Spring emanates. In the low ground of the mire numerous springs well up and are associated with peat mounds, including one about 5 m high called Pudding Pie Hill which has very little sulfate in the water. Farther east, in the middle of the mire, the sulfate levels are high at The Gallops, falling again at Gruntland Springs, which emanate from the Triassic Sherwood Sandstone in the east.

Ripon, Hall Garth Ponds, near Nunwick

These ponds are very similar in character to Hell Kettles. They include a sinkhole that collapsed in 1939 (Cooper, 1986) and several other sinkholes that have been "landscaped" into larger ponds of different shape. The 1939 sinkhole has artesian water welling up within it and high sulfate levels also suggest spring activity in the adjacent ponds. The geological situation is similar to that shown in Figure 2, with the Brotherton Formation (dark blue on Figure 2) present in the east wall of the sinkhole.

Ripon springs and ponds at Ripon Parks

Ripon Parks includes a number of ponds occupying very large sinkholes and a number of springs that emanate from the gypsum of the Edlington Formation and the glacial deposits. Despite the springs emerging next to small gypsum outcrops, very little sulfate was present. Similarly, the ponds situated in collapsed glacial deposits also had low sulfate levels.

Ripon town Spa Field and road bridge springs

These springs are located in a low part of Ripon where there are numerous peat bogs and abundant active subsidence features (Cooper, 1986, 1989, 1998, 2008a; Cooper and Saunders, 2002). Recent site investigation has proved sulfate-rich water in a peat bog that occupies part of the former Spa Field near the former Spa Well.

Spring Name	NGR E	NGR N	pН	Temp	Conduc- tivity	Concentrations mg/l				Analyst or reference
				°C	mS/cm	Ca ²⁺	SO ₄ ² -	HCO ₃ -	TDS	
Hell Kettles, Croft, Darlington: Croft Kettle (CK2) at 5m	428151	510844	7.75	11.2	1.680	480.9	1225.3	256.9	2148.2	Miller 2006
Hell Kettles, Croft, Darlington: Double Kettle (DK1) at 4.2m	428091	510912	7.76	14.7	1.500	404.3	1097.8	232.0	1904.3	Miller 2006
Hell Kettles: Oxen le Fields Borehole	428340	511210	6.93	15.8	1.250	257.4	533.4	283.9	1185.3	Env. Agen- cy (Miller 2006)
Neasham; Low Neasham Springs	431707	510709	7.2	12.7	N/A	135.0	12.0	317	N/A	Greenwood 2008
Croft: Sweet Well (Spa)	427879	509186	6.7	10.7	N/A	428.0	867.0	229.0	N/A	Greenwood 2008
Snape Mires; Pud- ding Pie Hill	427815	484458	7.6	13.5	0.161	58.7	32.4	N/A	416.4	Brown 2010
Snape Mires; The Gallops 1	428767	484395	7.34	12.0	0.320	548.9	952.5	N/A	1943.8	Brown 2010
Snape Mires; The Gallops 2	428794	484359	7.34	20.6	0.720	189.7	306.9	N/A	1305.2	Brown 2010
Snape Mires east; Gruntland Springs 1	428723	488409	7.26	10.0	0.320	211.4	228.3	71.2	698.2	Brown 2010
Snape Mires east; Gruntland Springs 2	428723	488409	7.26	10.0	0.315	247.9	338.1	83.4	948.4	Brown 2010
Snape Village; Mill House Spring 2	427408	484065	7.46	9.9	0.202	92.2	45.4	24.4	408.5	Brown 2010
Ripon, Hall Garth Ponds; 1939 sink- hole (N3) at 6.6m	431842	474707	8.03	10.2	1.700	490.7	1172.4	227.4	2001.0	Miller 2006
Ripon, Hall Garth Ponds; east pond (E3) at 0.8m	431895	474681	7.82	17.3	1.210	281.3	549.6	230.3	1146.6	Miller 2006
Ripon Parks, Queen Mary's Dubb at 4m	430662	474828	7.41	14.9	0.072	34.7	9.5	50.8	128.4	Brown 2010
Ripon Parks, Black Heath Pond at 1.4m	430435	474959	7.34	14.9	0.147	66.4	42.8	63.0	214.4	Brown 2010
Ripon Parks spring 4	430594	475472	8.27	11.6	0.220	122.9	55.7	91.5	368.4	Brown 2010

Table 1. Names, locations and main sulfate, calcium and bicarbonate compositions of springs in the study area. (Continued on following page.)

Table 1		Continued	from	previous	page.
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Spring Name	NGR E	NGR N	рН	Temp	Con- duc- tivity	Concentrations mg/l				Analyst or reference
				°C	mS/cm	Ca ²⁺	SO ₄ ² -	HCO ₃ -	TDS	
Ripon, Spa Field (Nr Spa Well at 431573 471607) at 1.6m	431505	471746					2015.0			Site investi- gation report
Ripon, Bridge foundations	431889	472039					1360.0			Thomson et al 1996
Ripon, Racecourse gravel pit (approx locality)	432950	469500					289.0			Thomson et al 1996
Ripon, Sharow spring	433041	470763	7.54	9.5	1.340	247.0	409.0	320.0		Simon War- wick pers. comm.
Knaresborough, Dropping Well spring	434766	456498	6.9	10.7	N/A	681.0	1360.0	298.0	N/A	Greenwood 2008
Knaresborough, Dropping Well tufa screen top	434773	456518	7.6	11.7	N/A	709.0	1420.0	264.0	N/A	Greenwood 2008
Brotherton; Burton Salmon - Lake outflow	448979	427269				178.7	65.8			P Murphy (1998, unpub.; high Cl.)
Brotherton: Byram - drainage ditch	448626	425162				256.1	358.3			P Mur- phy (1998 unpub.; high Cl.)
Askern; main lake inlet	456238	413583	7.1	13.8	N/A	610.0	1400.0	166.0	N/A	Greenwood 2008
Askern; main lake deep sinkhole (A1N) at 5m	456286	413505		17.5	N/A	561.0	1310.0	122.0	N/A	Greenwood 2008
Askern: Manor Bath (well)	456322	413525				433.0	947.0		2361.0	Bothamley, 1894 (page 351)
Askern; Lake borehole (location unconfirmed)						697.0	1172.0	306.0	N/A	Env. Agency (Greenwood. 2008)
Askern; Colliery borehole	455690	413640				585.0	1422.0	279.0	N/A	Env. Agency (Greenwood. 2008)
Askern; Manor Well at 0.9 m	456322	413525		9 to 17		594.0	1085.0			Brewerton 1818 (Green- wood, 2008)
Askern; Manor Well	456322	413525				573.0	1493.0			Lankester 1842 (Green- wood, 2008)
Askern; Charity Well	456197	413392				584.0	1251.0			Lankester 1842 (Green- wood, 2008)

Just to the east of this the new Ripon Bridge over the River Ure had sulfate-rich artesian water welling up in the foundation excavations and some of the local Quaternary deposits of sand and gravel were cemented with calcareous tufa, as are the gravels that occupy this part of the buried valley at Ripon (Cooper, 1986; Thompson et al., 1996). Nearby artesian springs were recorded in the bed of the river, and boreholes drilled for the bridge-site investigation had an artesian head about 1 m above river level. This water is fed from the higher ground to both the west and east as indicated in Figure 2, which is drawn through this area. Ripon has a spa hotel, but the water for this was piped in from Carboniferous strata several kilometers to the west.

Sharow Spring

Situated a little to the southeast of Ripon in a former glacial overflow channel, this spring has mixed water related to both gypsum dissolution in the Permian sequence below and water flowing through the Triassic Sherwood Sandstone to the east.

Ripon Racecourse

Water collected from the gravel pit ponds at Ripon Racecourse is high in sulfate and attests to spring activity from the underlying gypsum feeding sulfate-rich water into the gravel pit that is also fed by percolation from the nearby river. The location of the gravel pit is over the buried valley of the River Ure (Figure 2).

Knaresborough Dropping Well (petrifying)

The Dropping Well spring emerges from the Edlington Formation and its associated gypsum strata lying to the west of Knaresborough close to the contact with the underlying Cadeby Formation. The water is high in both sulfate and carbonate, the latter being actively deposited as a tufa ramp and screen below, in which artifacts are petrified as a tourist attraction (Figure 5). Several sinkholes are present in the fields that form the catchment to the spring. The spring above the tufa screen was sampled on 19th June 2008, it had rained heavily 6-7 hours previously and the flow was gauged at 5040 liters an hour.

Brotherton area springs

In the Brotherton area there are a number of sinkholes and several springs that feed into a small lake (Murphy, 2000): however, the water emanating from the lake has low sulfate levels (Table 1). Farther south, on similar Permian geology, a spring yields a moderate amount of sulfate, but also high levels of chloride, which may be anthropogenic or possibly related to chloride salts in the Permian sequence.

Askern springs and lake

Askern today has an ornamental lake next to the road in the middle of the village. The air photographs and the present sampling (Greenwood, 2008) show a number of sinkholes in the bed of the lake (Figure 6), but although sulfate levels were high in the lake they appeared to be related to water flow coming from a major inlet rather than artesian water coming up from the sinkholes. This might be because of groundwater pumping for mining and pollution control in the area. Historical maps show that in the past there were more ponds to the south of the present lake. These included the so-called Mather Pits that had very high sulfate levels and which did not freeze in the winter (Brewerton, 1818; Lankester, 1842; Bothamley, 1894).



Figure 5. The Dropping Well (petrifying spring) at Knaresborough.



Figure 6. Askern Lake showing the sinkholes within it as deeper water in the middle, southeast and southwest; west (left) edge of lake is 195 m long. Air Photography copyright UKP/Getmapping reproduced under license No UKP2006/01.

Interpretation

There is a close relationship between the presence of sinkholes that affect the Permian gypsiferous sequence and the locations of sulfate-rich springs. The driving mechanism is water flow from the catchment largely dominated by the Cadeby Formation dolomite sequence that underlies the gypsum formations and which has a large dipslope to the west of the main gypsiferous units. Water passing through this dolomite sequence is rich in magnesium and calcium carbonates. This type of commonion-water mixing is aggressive to gypsum, causing rapid dissolution resulting in numerous sinkholes (Klimchouk, 1996). The common-ion effect also dedolomitizes the dolomite at its contact with the gypsum (Bischoff et al., 1994) and changes it to a weak calcitic mesh that can also break down and cause subsidence. This process also helps to release calcium carbonate that is redeposited as tufa and tufa cements. The water analyses of the springs show different mixtures of sulfate and carbonate waters that appear to be controlled by the positions of the springs with respect to the Cadeby Formation dip slope, the low ground with the gypsum, and the higher ground formed by the overlying Triassic sandstone.

Artesian water is present wherever valleys cut through the Permian sequence. It is in these locations in the lower ground that the most aggressive dissolution is occurring and where the most active subsidence is happening. Consequently, where the valleys of the rivers Tees, Ure, Nidd, Wharfe, and Aire cut through the Permian escarpment, there are concentrations of sulfate-rich springs and sinkholes.

The distribution of the sinkholes is controlled by several factors. The western limit is the feather-edge boundary of the gypsum onto the underlying Cadeby Formation dolomite (Figure 2). The eastern limit is the down-dip transition from gypsum to anhydrite. This transition is largely controlled by the reduction in groundwater flow due to the sulfate-cemented nature of the aquifer units adjacent to the gypsum/anhydrite sequence. This gypsum to anhydrite transition occurs at a depth of about 100-120 m, giving the subsidence-prone belt a width of about 3 km (Cooper, 1986, 1988). Up to 40 m thickness of gypsum is present in the Edlington Formation and another 10 m or so above it in the Roxby Formation (Figure 3). The thickness of gypsum present means that if a significant part of it dissolves the resultant cavities and breccia pipes cannot generate enough breccia to bulk up and fill them, resulting in very large subsidence features at the surface (Cooper, 1986).

The study has shown that sulfate-rich springs are much more widespread than previously recognized. It also shows that sulfate concentrations similar to those recorded by Cooper (1986) commonly occur. The geology along the Permian escarpment and gypsiferous rocks is similar along the length of the outcrop. The superficial geology situation, with buried valleys cutting the sequence, is also repeated in several places (Figure 2). Cooper (1986, 1988) suggested models for the amount of gypsum dissolution in the Ripon area based on groundwater with a sulfate level of 1200 mg/l, as found in a local borehole in Ripon. The calculation presented by Cooper (1986) suggested an annual amount of around 120 cubic meters of gypsum being dissolved every square kilometer. The sulfate-rich spring information we present suggests that if similar infiltration rates occur along the Permian escarpment, then similar annual amounts of gypsum are being dissolved along most of the gypsum belt.

The presence of sulfate-rich springs also helps to indicate areas where there is very poor groundwater quality due to the high presence of sulfates. They also indicate areas where groundwater abstraction should be discouraged for purposes such as irrigation, both because of the acceleration of dissolution such as that described by Cooper (1988), but also because of the problems of subsidence caused by rapid fluctuations of the piezometric level. Within the gypsum-subsidenceprone area some farm irrigation boreholes have been implicated as the possible causes of subsidence in the immediate vicinity to them. Currently there is an acceleration in the desire to install ground-source heat pumps. The presence of sulfate-rich water and the likelihood of enhanced dissolution mean that within the gypsum belt only closed-loop systems should be considered (Cooper et al., 2011).

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GYPSUM KARST AND POTENTIAL RISK IN SITING WIND TURBINES IN BLAINE COUNTY, OKLAHOMA

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Abstract

Gypsum, a highly soluble rock, is readily dissolved to form karst features identical to those associated with limestones and dolomites. Investigations in Blaine County, in northwestern Oklahoma, evaluated potential problems that subsidence due to gypsum karst may pose for the proposed Watonga Wind-Power Project, a wind-turbine project just east of Watonga. Catastrophic collapse of a wind turbine is clearly unacceptable, and minor settlement could also be a risk. Differential settlement by even 3 cm across a 15-m-wide turbine foundation could lead to the turbine tilting out of tolerance, requiring remedial repairs.

Gypsum beds of the Permian Blaine Formation underlie all parts of the Project Area, at depths ranging from 10 to 45 m below ground level. The Blaine Formation here is about 29 m thick: it consists of four gypsum beds, each 0.6 to 4 m thick, interbedded mainly with red-brown shales. The Blaine is overlain by the Permian Dog Creek Shale and by unconsolidated Quaternary sands, clays, and gravels that may obscure karst features. Field studies, aerial-photo analysis, and literature review show that there is no evidence of gypsum karst in the Project Area.

Although lacking direct evidence of karst in or near the Project Area, we recognize there is some potential for subsidence due to dissolution of shallow gypsum. Additional mitigation of this risk can be achieved by placing wind turbines at sites where the gypsum beds are deepest: we believe that where gypsum is 25 m below ground level, or deeper, the risk related to gypsum karst is low. Placing turbines at sites where gypsum beds are less than 25 m deep would pose a medium or high risk. To minimize this risk, a map was prepared showing areas of low, medium, and high risk, related to potential gypsum karst.

Introduction

This study examines the surface and subsurface geology of an area just east of Watonga, in Blaine County, northwestern Oklahoma (Figure 1). The study area embraces nearly 400 km², including the 140-km² Watonga Wind-Power Project Area wherein approximately 160 wind turbines would be constructed. The study focuses on the thickness, distribution, structure, and depth of gypsum beds in the Permian Blaine Formation that underlie the Project Area.

Gypsum is a highly soluble rock. Generally, it is susceptible to being partially or totally dissolved by



Figure 1. Map of western Oklahoma showing location of Watonga Wind-Power Project and the wind-energy-resource potential at 50 m above ground level.

groundwater, and to developing karst features such as caves, sinkholes, and underground water courses that commonly are also found in limestones and dolomites (Martinez and others, 1998; Johnson, 2003a, 2008). Gypsum beds crop out just east of the Project Area, and dip gently to the southwest where they underlie all parts of the Project Area. Because of the potential for gypsum karst in western Oklahoma, the distribution and depth of the various gypsum beds is important in the siting of wind turbines because of the potential for collapse due to subsurface bedrock dissolution. A wind turbine located above a sinkhole, cave, or other karst feature could become unstable if there is any settlement of the ground.

The depth to the top of the uppermost gypsum in the Blaine Formation ranges from 10 to 45 m, and in most of the Project Area the depth is 25 to 35 m. We believe that where the depth is 25 m or more, such a site would pose a low risk for problems related to gypsum karst, because if there is karst in these Blaine gypsum beds below that depth it is unlikely that subsidence would reach up to and impact the land surface. We believe that karst in the Blaine gypsums at shallower depths would pose a higher risk for a wind turbine.

Western Oklahoma is a favorable area for windgenerated energy (Figure 1). According to the Oklahoma Department of Commerce (personal correspondence, 2012), as of May 2012 there are 20 wind projects operating in western Oklahoma, with a generating capacity of about 2300 megawatts, and an additional 5 projects are under construction, with a capacity of nearly 900 megawatts.

Geologic Setting

Outcrops of Permian rocks in the Watonga area include gypsum and shale beds of the Blaine Formation, overlain by the Dog Creek Shale (Figures 2, 3, 4). These are, in turn, overlain by Quaternary terrace deposits and alluvium. The Blaine Formation is about 29 m thick in the Watonga area, and individual beds of white gypsum range from 0.6 to 4 m thick (Fay and others, 1962; Fay 1964). Gypsum typically makes up about 25% of the formation; the remainder is mostly red-brown shale and several thin beds of dolomite. The thickest gypsum is the 4-m-thick Shimer Gypsum Bed at the top of the formation. The Blaine Formation dips gently to the south and southwest, beneath the Project Area, at a rate of about 2 to 4 m/km (about 0.1 to 0.2 degree).



Figure 2. Geologic map of the Watonga Wind-Power Project Area in Blaine County (Fay, 2010). Blaine Formation gypsum beds dip gently to the south and southwest (the strike and dip symbols) beneath the Dog Creek Shale and Terrace Deposits that mantle most of the Project Area.

The Dog Creek Shale generally is 50 to 58 m thick in Blaine County (Fay and others, 1962; Fay, 1964), but the upper part is eroded in the Project Area and only about 3 to 15 m of shale remains. The Dog Creek is principally red-brown shale (upper part of Figure 3), but it contains several thin beds of gypsum (0.5 to 2 m thick) in the subsurface southwest of the Project Area.

Above the Dog Creek Shale are Quaternary terrace deposits and alluvium deposited by the North Canadian River. They consist of non-cemented sands, clays, and gravels that generally are 10 to 20 m thick. All of the proposed wind turbines will be sited directly upon these Quaternary deposits where they overlie the Dog Creek Shale.

Methods of Study

A comprehensive review of the geologic literature to determine if karst features have been reported in Blaine County and nearby parts of Oklahoma was carried out. An aerial-photo study was also conducted to detect any possible karst features. Nearby outcrops of gypsum were



Figure 3. Exposure of the Shimer Gypsum Bed (white) at top of Blaine Formation and the overlying Dog Creek Shale (redbeds). Exposed in US Gypsum quarry about 20 km north of Watonga. Gypsum here is 4.5 m thick.

also visited to determine if there is any field evidence of karst features in or near the Project Area.

Additionally, electrical logs (also called "geophysical logs") of many petroleum test wells drilled within and near the Project Area were examined, 20 of which contained near-surface data on the thickness and depth of individual Blaine gypsum beds. The electric-log study enabled compiling a structure-contour map on the Shimer Gypsum Bed at the top of the Blaine Formation, and this was used to determine the depth to the top of the Blaine Formation gypsum beds beneath the Project Area.

Using all these studies and data, we compiled a "riskcategories" map (discussed below) to help minimize the possibility that gypsum karst will have an adverse impact on any part of the Project.

Literature Review

A State geologic map was prepared by Miser (1954), followed by detailed maps of the surface geology of Blaine County and the Watonga area by Fay and others (1962) and Fay (2010). These later maps show the outcrop area of gypsum beds in the Blaine Formation, as well as outcrops of the overlying Dog Creek Shale and the Quaternary-age terrace deposits and alluvium (Figure 2). In addition, Fay (1964) discussed the stratigraphy and character of the Blaine Formation and associated strata throughout northwestern Oklahoma. These three studies by Fay were most valuable for understanding the geology of the Project Area (see "Geologic Setting" above).

Gypsum karst has been described in thicker gypsum beds elsewhere in western Oklahoma by Myers and others (1969), Johnson (1989, 1990, 2003b), and Bozeman (2003). In addition, a number of gypsum caves in the Blaine Formation of western Oklahoma have been examined, mapped, and described by John and Sue Bozeman, of the Central Oklahoma Grotto, Oklahoma City: these reports have been released in <u>Oklahoma Underground</u>, which is a serial publication of the Central Oklahoma Grotto. As spelunking experts



Figure 4. Cross section showing thickness of gypsum beds of the Permian Blaine Formation in outcrops just east of the Watonga Wind-Power Project Area (after Fay and others, 1962). View looking to the southwest.

on gypsum caves of western Oklahoma, John and Sue Bozeman reported that they are not aware of any caves in the vicinity of the Watonga Wind-Project Area (personal communication, 2010).

Gypsum karst has not been recognized or described in the Project Area in any of the literature, probably because the gypsum beds here are quite thin and are interbedded with thicker, low-permeability shales that inhibit groundwater access to the gypsums. The one feature showing possible evidence of gypsum karst is the Foley sink, that formed 6.5 km west of the northwest corner of the Project Area in 1957 (Fay, 1958). The sink formed in Quaternary terrace deposits, about 30 m above the top of the Blaine Formation. Originally about 15 m wide and 5 m deep, the sinkhole has been filled by the landowner. No studies have been carried out to determine the true cause of the sinkhole. Fay also mentioned several older sinks located about 225 m northeast of Foley sink.

A statewide, general assessment of potential karst terrains in Oklahoma was made by Johnson (2003c). The study was preliminary, with only general data discussing the various potentially karstic rocks (limestone, dolomite, gypsum, and salt), and showing the general outcrop area of Blaine gypsums in northwest Oklahoma.

Aerial-Photo Study

Personnel at Barr Engineering in Minneapolis, MN, examined aerial photos of the Project Area taken in 2006 and stereo-image pairs from three dates (May 2006; November 1990; and April 1979). A number of linear drainage features are evident that extend in directions between N 20° E and N 30° E (oriented northeast to southwest), but field examination did not show that these features are related to sinkholes or voids.

The aerial-photo study also identified some ephemeral ponds as "potential sinkholes," but field studies did not confirm any evidence of sinkholes. Many closed depressions are present in the Quaternary terrace deposits that blanket the area. Inasmuch as these terrace deposits contain much wind-blown sand and silt, the land surface consists of many sand dunes that create a hummocky topography, with internal drainage flowing into many small depressions. Some of these depressions, at first glance, may appear to be related to sinkhole development or collapse structures, but there is no evidence that any of the small depressions have, in fact, resulted from ground collapse. The small ephemeral ponds present in some of the depressions appear to result from local runoff (from precipitation) into areas that have no external drainage.

Field Examination

Field studies have discounted the presence of "potential sinkholes" in terrace deposits, as suggested in the earlier aerial-photo study (see above). Also, gypsum exposures in outcrops and quarries near the Project Area were examined, and no evidence of karst features or voids was found. This observation agrees with the earlier findings of Fay and others (1962) and Fay (1964), and with recent discussions with John and Sue Bozeman (personal communication, 2010). The one exception is the Foley sink, described above, that is 6.5 km west of the Project Area. The Foley sink has been backfilled by the landowner and now is just a gentle depression in the ground.

Electric-Log Study

About 400 petroleum tests have been drilled in, and adjacent to, the Project Area. The electric logs of these wells were examined by Johnson, but only 20 of them contained data about the Blaine Formation or other rock layers present in the top 100 m of the borehole. Recognition of gypsum beds and associated rock types on electric logs is well established (Alger and Crain, 1966), and the senior author has conducted many studies using various types of well logs to identify, correlate, and map gypsum beds in the subsurface—some of the studies are in public documents (Johnson, 1967, 1985, 1993), and many others are in consulting reports.

On each of the 20 useable electric logs in the study area, individual gypsum beds (and interbedded shale units) that are at least 0.5 m thick can be identified readily (Figure 5). Recognition and identification of gypsum beds on the electric logs is confirmed by comparison and correlation with outcrops (Figure 4) just 3 km to the northeast. Correlation from outcrops to the electric logs shows that the overall thickness of the Blaine Formation, as well as the thickness of individual units, is quite uniform beneath the Project Area.

The principal result of the electric-log study is preparation of a structure-contour map that shows the elevation of the top of the uppermost gypsum (the Shimer Gypsum) of the Blaine Formation beneath the Project Area (Figure 6).



Figure 5. Electric logs of two wells showing depths (in feet) and log characteristics of gypsum beds in the Blaine Formation in (and near) the Watonga Wind-Power Project.

Results of Study

As a result of the foregoing studies, it is possible to use the structure-contour map and topographic maps to select sites for construction of wind turbines where the risk is low, with regard to possible gypsum karst.

Potential Karst Risks

Evaporite rocks, mainly gypsum (or anhydrite) and rock salt, are the most soluble of common rocks. They can be dissolved readily to form caves, sinkholes, and other karst features. Gypsum karst has not been documented in the Watonga area in the literature, probably because the gypsum beds here are quite thin and are interbedded with thicker, low-permeability shales that inhibit groundwater access to the gypsum. Evidence of gypsum karst would include surface and shallow-subsurface features, such as caves, sinkholes, disappearing streams, springs, collapse structures, and the dropping of drill bits and/or loss of drilling fluids while drilling through gypsum beds. None of these features have been found. As in any project undertaken in areas of soluble rock, karst can pose risks to wind turbines. If gypsum karst is present beneath the Project Area, it could cause subsidence or settlement of the overlying Dog Creek Shale and Quaternary sediments. This could result in tilting of, or damage to, the foundation of a turbine built above the karst feature. Even differential settlement of 3 cm across a turbine foundation that is 15 m wide could cause the turbine to tilt and require remedial repairs.

Based upon literature review, field investigations, and our other studies, there is no evidence of gypsumkarst features in outcrops in the Watonga area, or in the shallow subsurface beneath the Project Area. However, to further reduce the potential risk of gypsum karst on the Project, we recommend that wind turbines be placed at sites where the top of the Blaine gypsum beds is at least 25 m below the land surface.

Structure-Contour Map and Cross Section

The structure-contour map (Figure 6) was made by plotting the elevation of the top of the Blaine Formation



Figure 6. Structure-contour map showing elevation on top of the Blaine Formation gypsums beneath the Watonga Wind-Project Project Area. Contour interval is 6 m (20 feet). Cross section A—B shown on Figure 7.

on the outcrop and on electric logs of petroleum tests. The Blaine Formation dips gently and uniformly to the south and southwest at a rate of about 2 to 4 m/km (about 0.1 to 0.2 degree). This map is most useful because it shows the approximate elevation of the uppermost gypsum bed (Shimer Gypsum) beneath all parts of the Project Area, and the Shimer elevation can be subtracted from the elevation of the land surface to determine the approximate depth to the top of the Shimer Gypsum. If there is a potential for gypsum-karst features to impact the Project, these features would most likely be present in the shallowest and thickest gypsum—the Shimer Gypsum Bed. But all evidence presented indicates that there is no karst present in the Project Area.

A cross section (Figure 7) shows subsurface relationships between the Blaine gypsums and the overlying Dog Creek Shale and the Quaternary terrace deposits and alluvium beneath the Project Area. The cross section is based on outcrop information from Fay and others (1962 and Figure 4), and on the structure map on top of the Blaine Formation (Figure 6). In all parts of the Project Area where turbines might be constructed, they would be located upon Quaternary terrace deposits or alluvium. Immediately beneath these Quaternary deposits, remnants of the lower Dog Creek Shale are present and would separate the Quaternary deposits from the Shimer Gypsum. The Dog Creek Shale is a low-permeability barrier that provides added protection against karst by inhibiting the flow of groundwater from Quaternary sediments into underlying gypsum beds.

Risk Map

A schematic cross section shows possible karst conditions in gypsum, related to the depth of gypsum below the land



Figure 7. Cross section A—B through the Watonga Wind-Power Project Area showing the dip of strata and depths of gypsum beds of the Blaine Formation. Cross section based upon: Figure 6; outcrop data; two borings by Barr Engineering Co. (borings #87 and #76); and electric logs of oil-well tests (including Texaco, Horsley Unit "B" No. 1, shown in Figure 5). Line of cross section shown on Figure 6.



Figure 8. Schematic cross section showing low-, medium-, and high-risk karst zones, which are related to the depth of possible karstic gypsum in northwestern Oklahoma (modified from Johnson, 2003c).

surface (Figure 8). It is reasonable to expect that placing wind turbines at sites where the gypsum beds are 25 m deep, or deeper, would pose a low risk related to gypsum karst subsidence. Sites where the gypsum is more than 6 m, but less than 25 m, below the surface are sites of medium risk, and sites where the gypsum is 6 m, or less, below the surface are sites of high risk.

Using criteria cited above (25- and 6-m depths to gypsum), a risk map (Figure 9) was prepared by Barr Engineering personnel using a GIS program that compared the elevation of the land surface with the elevation of the Blaine Formation (Figure 6). This established the depth to the top of the uppermost gypsum bed in all parts of the Project Area.

These gypsum-depth/risk categories are considered to be conservative. Although there is no evidence of gypsum karst in the Watonga area, it is possible that dissolution of gypsum has occurred and has not yet been identified. At least 25 m of sand, clay, gravel, and shale between a wind-turbine base and the shallowest gypsum bed should provide sufficient protection from possible karst development and collapse structures, and turbine sites in those areas would be at low risk. Using these criteria and the risk map, it will be possible to locate any proposed turbine site in the low-risk area, and the medium- and high-risk areas can be avoided.

In most parts of the Project Area the uppermost gypsum is 25 to 35 m deep, and locally it is up to 45 m deep. Therefore, most of the area is considered to pose a low risk for problems related to gypsum karst.

Summary and Recommendations

Gypsum beds of the Permian Blaine Formation underlie all parts of the Watonga Wind-Power Project Area. Being a highly soluble rock, gypsum is readily dissolved to form karst features identical to those associated with limestones and dolomites. Settlement of a turbine foundation by even a couple of cm above gypsumkarst features could lead to tilting of the turbine out of tolerance and require remedial repairs. Therefore, we examined the local geology to evaluate whether gypsum karst could pose problems for the Project.



Figure 9. Risk categories at Watonga Wind-Power Project, based upon depth to the Shimer Gypsum at top of the Blaine Formation. Contour lines from Figure 6.

The Blaine Formation is about 29 m thick, and consists of four gypsum beds, each 0.6 to 4 m thick. The top of the gypsums is 10 to 45 m below ground level in the Project Area. The Blaine is overlain by the Permian Dog Creek Shale and by unconsolidated Quaternary sands, clays, and gravels that may obscure karst features. Field studies, aerial-photo analysis, and literature study show that there is no direct evidence of gypsum karst in the Project Area.

Examination of electric logs of petroleum tests enabled making a structure-contour map on top of the uppermost Blaine gypsum beneath the Project Area. This enabled us to prepare a cross section and risk map showing the depth to the top of gypsum, and enables us to determine sites where the risk due to gypsum karst would be low. We believe that those locations where the depth to gypsum is at least 25 m would be low-risk sites. We believe that the risk would be moderate where the depth to gypsum is between 6 and 25 m. The gypsum-karst risk would be high at those locations where gypsum is less than 6 m deep.

We suggest further evaluation of the potential for gypsum karst in the Watonga area by considering the following actions: 1) examine cores drilled through the Shimer Gypsum Bed in the Project Area to determine if there is evidence of dissolution in that shallowest and thickest gypsum bed; 2) conduct a survey of landowners within the Project Area to determine if any collapse structures, similar to Foley sink, have formed recently; 3) if such a collapse structure is reported by landowners, it should be examined by field work and core drilling to see if it is underlain by gypsum-karst features; and 4) conduct a survey of landowners where the Blaine Formation crops out just east of the Project Area, to determine if they have observed any karst-like features that might indicate gypsum dissolution.

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EVAPORITE KARST IN THE BLACK HILLS, SOUTH DAKOTA AND WYOMING, AND THE OIL PLAY IN THE WILLISTON BASIN, NORTH DAKOTA AND MONTANA

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Abstract

Subsurface red beds of the Permo-Triassic age Spearfish Formation in the Williston Basin has recently been touted as "another Bakken Oil Boom for North Dakota". The senior author, totally uninformed about the subsurface geology of North Dakota, was requested by INFOCAST* to discuss petroleum potential in the Spearfish based on his field experience in the outcrop belt of the Black Hills in neighboring Wyoming and South Dakota. That request was extended to a discussion of the surface and subsurface evaporite-karst features in four formations ranging from Pennsylvanian to Jurassic age. Dissolution of these rocks, which has resulted in sinkholes, caves, springs, breccia pipes, and subsurface collapse, has apparently gone on since the Black Hills was formed during the Early Tertiary, and continues today. The formation of salt-dissolution paleokarst in the Williston Basin and adjacent Powder River Basin has been documented to have occurred many times in the geologic past, between the mid-Paleozoic through the Tertiary. Reported subsurface collapse has affected rock characteristics, including local structure, fracturing, porosity, and permeability. These significant effects of evaporite karst in the Williston Basin, as well as in subsurface evaporite-bearing sequences nationally, should be of concern to any oil exploration efforts, as well as for surface infrastructure development such as pipeline right-of-way.

Introduction

Large areas of the United States are underlain by evaporite deposits that mainly consist of gypsum, anhydrite, and salt (Figure 1). Holocene dissolution has created abundant karstic features at the surface and near-surface in many areas. Dissolution has also occurred during intervals in the geologic past, thereby creating many intervals of paleokarst throughout Paleozoic-lower Mesozoic-age strata in the Rocky Mountains and adjacent mid-western United States. Many of the evaporite intervals lie within or between petroleum-bearing horizons, and karstic development within them are of concern to oil and gas exploitation. In this paper we discuss two areas of interest: 1) surficial evaporite karst in the Black Hills of Wyoming and South Dakota, and its extension into the subsurface in the Williston Basin of North Dakota, and 2) a paleokarst horizon in the upper Madison Limestone of Wyoming and South Dakota, and its possible extension into the Williston Basin.

Oil and gas potential in the Williston Basin of North Dakota and adjacent Saskatchewan, Canada, has recently attracted considerable attention, with particular interest in the organic shales of the Bakken Formation of Devonian age. With the use of hydraulic fracturing to increase the release of oil and gas from these source rocks, other stratigraphic units in the basin, such as the Spearfish Formation of Permian and Triassic age, have been touted as possibly being additional unconventional oil plays in the subsurface of North Dakota (LeFever, 2011). In contrast to the reducing environment of deposition of the dark organic-rich rocks in the Bakken, the Spearfish is a red-bed sequence deposited in an oxidizing environment. The Spearfish has been prospected in northernmost North Dakota, more than 500 km (340 mi) from the nearest outcrops in the northern Black Hills (Figure 2). It is not exposed at the surface in North Dakota, so one of us (Epstein) was requested to discuss the geologic characteristics of that formation in its nearest outcrop belt of the northern Black Hills of South Dakota and Wyoming.

The Spearfish Formation and evaporite karst in the Black Hills

The Black Hills is an asymmetric uplift about 210 km (130 mi) north-south and 100 km (60 mi) east-west. It is cored by Precambrian age metamorphic rocks that are

*http://www.infocastinc.com/downloads_pdf/bakken11_pre.pdf (accessed 11/5/2012)



Figure 1. Map showing the distribution of outcropping and subsurface evaporite rocks in the United States and areas or reported evaporite karst. The 32.5-in. mean-annual-precipitation line approximates a diffuse boundary between eastern and western United States karst terrains (from Epstein and Johnson, 2003).

surrounded by shallow-marine to nearshore terrestrial sedimentary rocks of Paleozoic and Mesozoic age which dip away from the center of the dome (Figure 3). Gypsum and anhydrite are found in rocks ranging in age from Mississippian to Jurassic (Figure 4). The "Limestone Plateau" located outbound from the central Black Hills core, comprises rocks of the Madison Limestone (Pahasapa Limestone of other reports) and the Pennsylvania age Minnelusa Formation. Most surface exposures of the Minnelusa contain abundant karst features resulting from dissolution of anhydrite at depth. The Madison contains brecciated rocks resulting partly from similar gypsum dissolution, as well as world-class limestone caves. The "Red Valley" encircles the Black Hills resulting from the erosion of siltstones, shales, and gypsum in the Spearfish Formation. Resistant sandstone of Cretaceous age forms the hogback that encircles the Black Hills and defines its outer physiographic perimeter. Below those sandstones is a thin gypsum bed in the Gypsum Spring Formation of Jurassic age. Much of the information about the karst in the Black Hills presented here is summarized from Epstein (2003) and Epstein and others (2005).

The Spearfish Formation in the Black Hills ranges to slightly more than 240 m (800 ft) in thickness, consisting

predominantly of red, planar-bedded and laminated shale, siltstone, and very fine-grained sandstone, with interbedded gypsum abundant at varying horizons (Figure 5). Bedding is generally sheet-like, although lenticular beds and ripple laminations are not uncommon. Salt casts have been reported (Sabel, 1984). These sedimentary features indicate that the Spearfish was deposited in a hot and arid climate on low-gradient coastal plains and nearshore hypersaline mudflats bordering evaporite basins.

Sinkholes are abundant in the northern Black Hills. They range in size from small shallow pits and solutionallywidened joints (Figure 6) of as little as several feet to as much as much as 140 m (460 ft) across (Figure 7). The Vore Buffalo Jump shown in Figure 7 is rimmed by several convoluted, disjoined, and disrupted gypsum beds 2.5-3.0 m (10 ft) thick. No gypsum is seen at the bottom of the sinkhole, which is probably less than 15 m (50 ft) above the underlying Minnekahta Limestone. The Minnekahta crops out along the service road about one mile to the west where a 1.2 m (4 ft) thick bed of gypsum lies at the base of the Spearfish (Figure 8).

The largest sinkhole in the northern Black Hills is about 140 m (460 ft) across, occurs at the base of the



Figure 2. Geologic map of parts of North Dakota, South Dakota, Wyoming, and Montana. The outcrop area of the Spearfish Formation in the Black Hills is located approximately 530 km (330 mi) from the Spearfish oil play in Bottineau County, North Dakota. The Black Hills is a domal structure cored by Precambrian rocks in the center (orange). It is encircled by uplifted and erosionally breached Paleozoic to Cretaceous rocks. Red beds and evaporite deposits of the Spearfish Formation (red) form a valley nestled between the hogback of Cretaceous age sandstones and plateau of underlying carbonate rocks, including the Madison Limestone of Mississippian age. The surface rocks in the western part of North Dakota are dominated by Tertiary rocks (solid green) overlying Cretaceous sediments to the west.

Spearfish Formation (Figure 8). It is underlain by a 1.2 m (4 ft) thick bed of gypsum which in turn overlies the Minnekahta Limestone; both dip gently underneath the sinkhole. The limestone outcrop closest to the sinkhole contains a small collapse opening in a blind valley. A smaller sinkhole (inset of Figure 8) opened in 1985, and was observed by local ranchers who heard running water in a cavern that extended horizontally beyond the limits of their flashlight beam (Ted Vore, oral communication, 1999). This running water at the base of the Spearfish is deemed to be partly responsible for dissolution and collapse. However, the four-foot-thick gypsum bed in the basal Spearfish seems to be too thin to account for all the observed depth of the collapse.



Figure 3. Generalized diagram showing the geology and geomorphology of the Black Hills, Wyoming and South Dakota. Modified from Strahler and Strahler (1987), with permission.



Figure 4. Stratigraphic column showing distribution of gypsum and anhydrite in the northern Black Hills.
Figure 5. Typical exposures of the Spearfish Formation in the Black Hills, South Dakota and Wyoming. (A) White gypsum interbedded with red shale and siltstone about 15 km (10 mi) southeast of Newcastle, Wyoming.

(B) Planar- bedded red beds overlain by shales of the Stockade Beaver Member of the Sundance Formation (dashed line), one mile northeast of Beulah, Wyoming. A bed of gypsum, about 3 m (10 ft) thick, comprising the entire Gypsum Spring Formation a few miles to the east of this locality, is missing here. This is the closest exposure of the



Spearfish Formation to the Spearfish oil play in northern North Dakota. (C) Fining-upward sequences of very fine-grained sandstone, siltstone and shale in Devil's Tower National Monument, Wyoming. (D) Spearfish mudcracks 13 km (8 mi) northwest of Spearfish, South Dakota.

The Spearfish Formation in the northern Black Hills is as much as 250 m (820 ft) thick and contains several intervals of gypsum in the lower 60 m (200 ft). Anhydrite, which probably was the original form of calcium sulfate to be deposited in the Spearfish, undergoes about a 40 percent expansion when hydrated to form gypsum. As a result, the gypsum is commonly highly folded (Figure 9A, B). It also becomes mobile, being injected into irregular fractures as thin veinlets, generally less than 2 cm (1 in) wide in the confining beds above and below (Figure 9C). Thus, the lower 60 m (200 ft) or so of the Spearfish has developed a secondary fracture porosity resulting in appreciable ground water flow into water wells. Perched water tables with springs below zones of gypsum in fractured red beds are present in several places in the Black Hills. Gypsum beds are lacking in the upper 180 m (600 ft) of the Spearfish. Therefore, bedding is not disturbed by gypsum expansion, and the interval is a confining layer.

Breccia pipes are common in the Black Hills, including in the Spearfish Formation (Figure 10). These pipes consist of chaotic blocks in a matrix of rocks of the enclosing formations and they commonly extend *below* the base of the Spearfish. The large sinkholes in the lower Spearfish shown in Figures 7 and 8 contain



Figure 6. Small solution openings near Beulah, Wyoming.(A) Circular sinkholes about one meter across, with remnant gypsum present in thebottom.(B) Soil collapse along a solution-widened joint that extends downslope towards a creek.



Figure 7. Two sinkholes located 5.6 km (3.5 mi) west of Beulah, Wyoming, and immediately north of Interstate 90. (A) Sinkhole with a laterforming smaller internal sinkhole at arrow. (B} The "Vore Buffalo Jump" is an 18-m (60 ft)-foot deep sinkhole. More than 300 years ago the Native Americans stampeded bison over the steep rim into the hole. As many as 20,000 beasts were butchered for food. The site is now a major archeological dig by the University of Wyoming (http:// www.vorebuffalojump.org Accessed 11/13/2012/).



Figure 8. Karst features located immediately northwest of the Vore Buffalo Jump shown in figure 7. A deep sinkhole (see inset photo) lies within a larger, 140 m (460 ft) wide, flat-bottom sinkhole in center of the photo. Another sinkhole lies in the lower right corner. A conspicuous gypsum bed lies immediately above the Minnekahta Limestone and also underlies the sinkholes. Another gypsum bed lies above and to the north of the sinkholes.



Figure. 9. (A) Contorted gypsum resembling tectonic folds in the Spearfish Formation, Red Valley of the southwestern Black Hills, southeast of Newcastle, Wyoming, resembling tectonic folds. (B) Disrupted gypsum near Beulah, Wyoming. (C) Gypsum-filled fractures extending above and below contorted gypsum bed in the uppermost Spearfish Formation, along State Route 71 about 15 km (9 mi) southwest of Hot Springs, South Dakota.

some gypsum interbedded with the red beds. However, the bottom of the sinkhole is near or at the base of the formation, suggesting that the solution collapse is not



Figure 10. Resistant pinnacle-forming breccia pipe in the Spearfish Formation, about 24 km (15 mi) west of Hot Springs, South Dakota. The breccia pipe occurs about 100 m above the dissolved anhydrite in the Minnelusa Formation. Some sandstone clasts were derived from the overlying Sundance Formation, more than 30 m (100 ft) above.

entirely the result of dissolution of the local gypsum, but additionally due to removal of evaporites at greater depth.

The top of the Minnelusa Formation lies about 45 m (150 ft) below the base of the Spearfish Formation. It is about 150 m (500 ft) thick in the northern Black Hills and consists of dolomite, sandstone, and shale with anhydrite being prevalent in the middle part. The anhydrite is mostly absent in outcrops due to removal by solution in the subsurface. The solution of anhydrite and consequent formation of voids in the Minnelusa at depth resulted in foundering and fragmentation of overlying rocks, thereby producing extensive disruption of bedding, a regional collapse breccia, many sinkholes, and breccia pipes and pinnacles (Figure 11). The collapse breccia consists of angular clasts of all the local rock types in a sandy matrix that is generally cemented with calcium carbonate. The vuggy secondary porosity of the collapse breccia, along with the porous sandstone makes the upper half of the Minnelusa an important aquifer in the Black Hills.

Proof that collapse subsidence extended upward from the Minnelusa into the Spearfish is afforded by collapse observed within the thin intervening Minnekahta Limestone as seen near the sinkholes in Figures 7 and 8. Along Redwater Creek the Minnekahta is exposed in a 600 m (2000 ft) low cliff where numerous sinkholes are present and the unit is extensively brecciated, and the underlying Opeche Shale is also disrupted (Figure 12). This observation suggests that collapse structures in the Minnelusa extend upward through the Opeche and Minnekahta into the Spearfish.



Figure 11. Collapse structures in the Minnelusa Formation. Top photo is split into two segments at the dashed match line, showing the upper half of the Minnelusa Formation in Redbird Canyon, South Dakota, 16 km (10 mi) southeast of Newcastle, Wyoming. All beds are disrupted and mostly brecciated. Sinkholes and caves dot the canyon wall. Bottom photo shows Cold Brook Canyon, just west of Hot Springs, South Dakota. The upper half of the formation is brecciated with through-going breccia pipes (arrow). The lower half of the formation is not brecciated. Collapse was due to removal of many tens of meters of anhydrite in the subsurface prior to exposure of the canyon wall within the covered slope in the middle of the photo.

While breccia pipes and sinkholes may extend upward from the Minnelusa Formation into overlying formations, the evidence also suggests that sinkholes in the Spearfish may not necessarily be directly connected to pipes in the underlying Minnelusa. Abundance of sinkholes in the lower Spearfish suggests that there lurks a labyrinth of cavernous passageways developed as gypsum dissolved at the base of the formation while collapse extended upwards into the underlying Minnekahta Limestone.

Figure 13 shows the suggested systemic development and relationships of surface and subsurface karst features within and between the Minnelusa Formation, Opeche Shale, Minnekahta Limestone, and Spearfish Formation in the Black Hills. Groundwater in all units is generally under artesian-flow conditions. Groundwatr dissolution of subsurface anhydrite in the Minnelusa, as well as in the underlying Madison Limestone, has caused collapse features in the Minnelusa, commonly seen on canyon walls. Breccia pipes and some sinkholes have extended upwards into rock at least 120 m (400 ft) above the Spearfish. Local extensive disruption in the Minnekahta precedes groundwater flow along the gypsum in the basal Spearfish, creating the sinkholes in that formation. Karst development evolved continuously after the Black Hills was uplifted and exposed to erosion since the Late Cretaceous/Early Tertiary. Artesian groundwater conditions result from direct infiltration of rainfall and snow melt at high altitudes of the central Black Hills which flow outward and downdip through the rimming sediments, including the Madison and Minnelusa. Dissolution and removal of the anhydrite in the Minnelusa, progresses in a downdip direction



Figure 12. Collapse sinkhole (between dashed line) in a zone of brecciated Minnekahta Limestone, along Redwater Creek, 1.6 km (1 mi) southeast of the sinkholes seen in Figure 7. Inset shows details of the breccia.

with groundwater flow resulting in collapse breccias, breccias pipes, and resurgent springs that are developed at the site of (Figure 14).

As the Black Hills region is slowly lowered by erosion of the anhydrite-dissolution front in the subsurface, the Minnelusa moves downdip and radially away from the center of the uplift. As a result, resurgent springs will dry up and new ones will form with the downdip migration of the dissolution front as the geomorphology of the Black Hills evolves (Figure 14). Abandoned sinkholes on canyon walls (Figure 11) attest to the former position of the dissolution front. Groundwater has dissolved the anhydrite in the Minnelusa, but it is present in the subsurface, therefore a transition zone must be present where dissolution of anhydrite is currently taking place. Consequences of this model suggest that present resurgent springs will eventually cease to flow while new springs should develop in a downdip direction within the regional hydraulic gradient of the Black Hills. Solution of anhydrite in the Minnelusa probably began soon after the Black Hills was uplifted in the Early Tertiary, and it continues today.

Paleokarst in the Madison Group The Charles Formation, which forms the upper part of the

largely limestone and dolomite succession of the Madison Group, contains a remarkable intrastratal paleokarst. This stratigraphic interval is particularly well-exposed within the canyon of the Bighorn River in eastern Wyoming (Figure 15). It has an areal distribution extending across the Williston Basin in North Dakota and far to the southwest into the Bighorn Basin of Wyoming and Montana (Figure 16; Peterson, 1987; Sando, 1995). In the Black Hills, this paleokarst horizon is exposed within numerous cave systems such as Wind Cave and Jewel Cave. This extensive intrastratal paleokarst horizon contains abundant evaporite strata-mainly anhydrite and gypsum. Geologic studies of this interval show that it formed from groundwater migration and solution of evaporite minerals in an artesianflow system not unlike what has been documented to occur today in the western Black Hills. Collapse brecciation of cavernous solution voids has since been filled with finegrained silt and clay that is cemented with late calcite cement (Palmer and Palmer, 2008). Characteristics of this paleokarst horizon are similar to those described above for the Minnelusa Formation in the Black Hills.



Figure 13. Generalized cross section showing common karst features in the Beulah area, Wyoming. Features include sinkholes, cavernous gypsum in the basal Spearfish Formation, outcropping sinkholes in the Minnekahta Limestone, breccia pipes and dissolution zone at the top of the Minnelusa Formation, and artesian flow direction from the Minnelusa Formation and the Madison (Pahasapa) Limestone. Where the potentiometric surface is below ground level, sinkholes are dry; where it is above ground level, sinkholes contain emergent springs.



Figure 14. Generalized cross section showing the downdip migration of the anhydrite dissolution-front in the Minnelusa formation. Cox Lake and other resurgent springs are near the position of the dissolution front. As the front moves downdip with continued solution of the anhydrite, and as the Black Hills is slowly lowered by erosion, these sinkholes and related collapse structures are left abandoned on canyon walls (see Figure 3).



Figure 15. Exposure of paleokarstic breccia due to evaporite dissolution in the upper Madison Limestone. Exposure is within the Bighorn Canyon in eastern Wyoming. The outlined reddish layer contains abundant brecciated clasts of dolomite with vugs of anhydrite and gypsum. The red matrix is fine silt and clay cemented with late calcite. Layer thickness varies between 3 to 6 m (10 to 20 ft).



Figure 16. Generalized west-east structural stratigraphic cross section from the Bighorn Mountains, Wyoming, to north–eastern North Dakota. Modified from Peterson, 1988. Green color indicates units with significant evaporites, especially salt (compare with Figure 17). Blue color indicates the Bakken Formation.

The presence of this paleokarst horizon in the Madison Group suggests that the processes forming surficial karst today due to evaporite solution at depth have occurred multiple times in the geologic past within these evaporitebearing rocks. Exposures of such ancient solutioncollapse features can provide insight for understanding possible geologic structures and characteristics within deeply buried evaporite horizons that are experiencing solution in the Williston Basin.

Salt dissolution in the Williston Basin

The Williston Basin is a large intracratonic structural downwarp in North Dakota and eastern Montana, extending into Canada, and lying immediately north of the Black Hills of Wyoming and South Dakota (Figure 1). Deposition was intermittently continuous since the Middle Cambrian, with a total accumulation of about 4,900 m (16,000 ft) of sediment (Gerhard et al., 1990). Sedimentation rate kept pace with basin subsidence rate, so deposition mainly occurred in shallow water and in recurring evaporite basins. Transgressive and regressive cycles are numerous; pinchouts and disconformities are abundant (Peterson and MacCary, 1987, Figure 5). More than a dozen periods of evaporite deposition characterize the stratigraphic section (Figure 17). LeFever and LeFever (1995) recognized 24 major and minor salt beds within the basin. In contrast to the rocks in the Black Hills, halite and potash salts are common. The transition from salt in North Dakota to anhydrite, gypsum, and minor interbedded dolomite in many Black Hills formations marks the boundary between North Dakota evaporite basins to a shelf/sabkha environment in South Dakota and Wyoming.

Peterson (1995) presented a stratigraphic chart showing the occurrence of 12 hydrocarbon source beds and 15 reservoir rocks in the Williston Basin.

In the Williston Basin evaporites are commonly interbedded with petroleum source rocks. These evaporites may form seals and traps, or their karstic effects may disrupt stratigraphic continuity and disrupt the integrity of a reservoir. Subsurface dissolution features similar to those in the Black Hills has been documented in the Williston and nearby Powder River Basins. Bachu and Hitchon (1996, p. 253) noted the high salinity of formation waters, due partly to dissolution by fresh water in many of the Paleozoic aquifers.



Figure 17. Chart comparing the Devonian-Jurassic stratigraphy in the Black Hills, South Dakota, and Williston Basin, North Dakota. Formations with significant evaporites, especially salt, and some with more than one horizon, are in green (compare with Figure 16). Modified from Fahrenbach and others, 2010. See also: figure 1 in LeFever (2012); figure 2 in Burrus and others (1996); and figure 4 in Peterson (1988).

The modern regional flow path of formation waters is generally towards the east and northeast, emanating from the recharge areas in the Bighorn and Big Snowy Mountains and the Central Montana uplifts and Black Hills: a somewhat similar pattern to that shown in Figure 14 (Bachu and Hitchon, 1996, Figure 10). Salt thickness throughout the Williston Basin locally can be quite variable in thickness, apparently related to uneven dissolution due to several factors. Salt dissolution can be recognized by comparing thinning of salt in isopach maps in relation to overlying thicker compensating sediments that filled in the resulting hollow. The irregular thickness of the Dunham Salt in the Jurassic age Piper Formation occurs in isolated lenses due to dissolution (LeFever and LeFever, 1995). They also noted significant thicknesses of salt in the subsurface Spearfish Formation in the southwest corner of North Dakota. No salt is exposed at the surface in the Black Hills, although salt is known in springs along Salt Creek about 14 KM (8.5 mi) north of Newcastle, Wyoming, along US 85. At this location a roadside sign indicates that Darton, in 1904, determined that salt comprised 5 percent of the water there; about four percent salt was reported by Brobst and Epstein (1963). During the late 1800's significant quantities of salt were produced by evaporation. Whether that salt comes from the Minnelusa or the Spearfish is not known, but it does show that evaporite dissolution in the subsurface is ongoing.

The thickness of the Spearfish Formation in the northern Black Hills, close to the North Dakota border, varies from 190 to 268 m (625 to 879 ft) in water wells within the borders of two 7.5-minute quadrangles (Epstein, J.B., unpub data). This suggests that the gypsum, and possibly unrecognized salt, has been removed to create the discrepancy. Parker (1967) noted similar salt-thickness variations within short distances in several different units, such as the Middle Devonian Prairie Formation and Permian and Triassic age rocks of the Minnelusa Formation, Opeche Shale, and Goose Egg Formation (~Spearfish).

Several authors have recognized a slow-moving dissolution front that reduced the original depositional boundary of an individual salt deposit, such as in the Jurassic age Piper Formation (LeFever and LeFever (1995). Seismic data was used by Hamid and others (2004) to delimit the southern margin of evaporite in the Middle Devonian Prairie Formation, which is very complex due to dissolution removal of salt and brecciation.

A correlation exists between of areas of salt dissolution and the presence of faults and fractures that extend down into the Precambrian basement, and that were reactivated in the Paleozoic. These faults allowed fluid to move up into the salt bed from aquifers below. Salt removal was also intermittent, generally with long periods of no perceptible dissolution (Parker, 1967; Holter, 1969; LeFever and LeFever, 1995).

Holter (1969) identified solution-collapse breccias in cores in the Prairie Formation in Saskatchewan by the very poor sorting of angular rock fragments. The material in the lower part of the brecciated units are fine grained, apparently a residue from salt solution. Breccia deposits extend laterally beyond the present limits of salt, suggesting a migrating salt front as dissolution progresses in the direction of fluid flow. Dissolution of evaporites (salt) in the Williston Basin requires a hydrostatic head that allows ground water to dissolve and carry the salt in solution upwards, as well as tectonically induced fractures to tap fresh-water aquifers below the salt (Parker, 1967). Breccia pipes (dissolutioncollapse structures (filled stopes and chimneys)) may have formed along the edges of salt-dissolution fronts, extending vertically upward from several salt horizons and terminating at various unconformity horizons (Burke, 2001). If breccia pipes can be identified in the Williston Basin, they could be the locus for upwardflowing water as well as hydrocarbons. They may also affect the porosity of surrounding rocks by either creating solution voids or depositing cements. Breccia pipes in the Minnelusa of the Black Hills have high permeability and have been described as pathways for uranium-rich fluids (Gott and others, 1974). Breccia pipes in the Black Hills are also known to extend more than 300 m (1,000 ft) upwards from their source beds in the Minnelusa, suggesting considerable vertical interconnection in the sedimentary succession.

Subsurface solution collapse can affect important rock characteristics for petroleum development, such as fracturing, porosity, and permeability. Several studies have linked the dissolution of the thick Silurian to Jurassic age salt deposits in the Williston Basin to petroleum reservoir development. Salt and evaporite dissolution can also form stratigraphic and unconformity traps (LeFever, 2011, 2012) and salt collapse, halite plugging, incomplete anhydrite or residue seals, and dolomitization have affected or destroyed potential reservoirs (LeFever and LeFever, 1995).

The age of salt dissolution may be determined by the age of overlying sedimentary deposits that have been thickened due to in-filling of downwarps due to salt removal and collapse. Using this criteria Parker (1967) described the age of salt dissolution in different units in the subsurface of Wyoming, North Dakota, and Montana: Late Devonian through Mississippian for the Middle Devonian age Prairie Formation, and a Jurassic age for the Minnelusa Formation, Opeche Shale, and Goose Egg Formation.

Rasmussen and Bean (1984) concluded that the salt in the Ervey Member of the Goose Egg Formation in the Powder River and Williston Basins was removed by dissolution in Middle-Late Jurassic and Early Cretaceous time. Fractures extending from the basement controlled movement of groundwater and solution. Orchard (1987) showed that salts in the Mississippian age Charles Formation pinches out abruptly and are mostly missing over the Poplar Dome in the western part of the Williston Basin of Montana, while non-salt beds are continuous and exhibit little change in thickness. He attributed this to removal of the uplifted salt by ascending water along fractures that developed during Tertiary Laramide uplift. LeFever and LeFever (1995) concluded that the irregularities in thickness of the Pine Salt in the Spearfish Formation in the southwestern half of the basin were caused by dissolution during the Late Jurassic-Early Cretaceous and may have been similarly affected during the Late Cenozoic. LeFever (2011) also noted numerous times of salt removal in the Devonian Prairie Formation, including Middle and Late Devonian, Mississippian through Jurassic, pre-Cretaceous, and even Late Pleistocene to Recent.

Conclusions

Dissolution of gypsum and anhydrite in several stratigraphic units in the Black Hills, South Dakota and Wyoming, has resulted in development of a variety of both modern and paleo-karst features, including regional collapse breccias, breccia pipes and pinnacles, sinkholes, and extensive disruption of bedding. Evidence of recent collapse includes fresh scarps surrounding shallow depressions, recently formed sinkholes, and sediment disruption and contamination in water wells and springs. Anhydrite dissolution in the Minnelusa Formation probably dates back to the Early Tertiary when the Black Hills uplift commenced, and it continues today as an anhydrite dissolution-front in the subsurface Minnelusa moves downdip and radially away from the center of the Black Hills uplift. Over time, sinkholes and artesian springs associated with the migrating dissolution front

will dry up and new ones will form as the geomorphology of the Black Hills evolves. Abandoned sinkholes and breccia pipes that are preserved in cross section on canyon walls attest to the former position of the dissolution front. The Spearfish Formation, mostly comprising red shale and siltstone, has developed secondary fracture porosity due to considerable expansion during the hydration of anhydrite to gypsum. Many of the evaporite-karst features that are readily visible in the Black Hills have also been reported or suggested in the subsurface Williston Basin, including collapse breccias, breccia pipes, sinkholes (solution depressions), and progressive salt-margin retreat along a dissolution front. Petroleum geologists contemplating the effects of salt karst in the oil patch in North Dakota would do well to examine the excellent karst exposures in the Black Hills of South Dakota and Wyoming. As an additional thought, a better understanding of the distribution of karst-controlled surface-collapse features in the Black Hills would be helpful in planning interstate pipeline routes from the expanding oil fields in North Dakota.

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VARIATIONS IN EVAPORITE KARST IN THE HOLBROOK BASIN, ARIZONA

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Abstract

At least six distinct forms of evaporite karst occur in the Holbrook Basin—depending considerably on overburden and/or bedrock type. Early Permian evaporites in the 300-m-thick Corduroy Member of the Schnebly Hill Formation include halite, sylvite, and anhydrite at depths of 215-250 m. Karst features result from collapse of overlying Permian and Triassic strata into underlying salt-dissolution cavities.

Evaporite karst occurs primarily along the 100+ kmlong dissolution front on the southwestern edge of the basin, and is characterized by numerous sinkholes and depressions generally coincident with the axis of the Holbrook Anticline—in reality a dissolution-collapse monocline. "The Sinks" comprise ~ 300 individual sinks up to 200 m across and 50 m deep, the main karst features along the dissolution front. Westerly along the dissolution front, fewer discrete sinkholes occur, and several breccia pipes are believed to be forming. Numerous pull-apart fissures, graben-sinks, sinkholes, and broad collapse depressions also occur.

A newly recognized subsidence/collapse area of some 16 km² occurs in the western part of the basin, northward from the extension of the Holbrook "anticline." The Chimney Canyon area is some 12 km east of McCauley Sinks, a postulated breccia pipe exemplified in, and possibly manifested in at least four other closed depressions. Interferometric Synthetic Aperture Radar (InSAR) data of one depression shows active subsidence of ~4 cm/yr.

Karst formation is ongoing, as shown by repeated drainage of Dry and Twin Lakes into newly opened fissures and sinkholes. These two playa lakes were enlarged and modified in recent years into evaporation impoundments for effluent discharge from a nearby pulp mill. Four major drainage events occurred within these playa reservoirs during the past 45 years, collectively losing more than 1.23×10^7 m³ (10,000 acre-feet) of water and playa sediment. Drainage occurs through piping into bedrock joints in Triassic Moenkopi Formation (sandstone) in the bottom and along the margins of these playas. Effluent discharge has been discontinued into these playas, although recurring precipitation can fill the basins.

Introduction

Evaporite karst in the Holbrook Basin of northeastern Arizona occurs above interstratal bedded evaporites, principally halite, in Permian sediments. The karst displays a variety of geomorphic features common to many carbonate-karst terrains (Jennings, 1985), including more than 500 sinkholes, fissures, depressions, and other features (Neal et al., 1998). The karst features are the subject of environmental concern because of increasing encroachment of residential and industrial development, and because of potential groundwater influx through surface karst openings.

Bahr (1962) was among the first to show that karst formation is still active, noting that a sinkhole visible on 1953 air photos had not existed 17 years earlier. New fissures and sinkholes have been observed many times since, with more recent activity in December 1995 on the south side of the collapse basin, and during 1996-8 in Dry Lake Valley, a major collapse depression that contains several artificially impounded playa lakes.

Local ranchers have continued to report periodic sinkholes forming when the valley floor flooded. These karst features are among the lesser known geomorphic curiosities in Arizona, but surely one of the most spectacular displays of evaporite karst in the United States! Newly discovered (2012) InSAR anomalies in the Chimney Canyon area reveal active subsidence depressions that are described by Conway and Cook (2013, this volume). Active karst is likely to play a major role in the development of the Holbrook Basin.

Evaporite Deposition and Geologic Setting in the Holbrook Basin

Holbrook Basin evaporites originated in an inland sea, part of the Pangean supercontinent and perhaps not so different from today's Caspian Sea, having encroached from the oceanic south for some five million years during early Permian time-280 mya. The Paradox and Eagle Basins in the Four Corners area to the northeast had formed 30 my earlier, but from a northern access to open ocean. The current cycle of plate tectonics did not begin to break up Pangea until ~195 mya. Holbrook Basin evaporite deposition, while roughly equivalent to Supai Group rocks in Grand Canyon, existed only in present-day northeastern Arizona and extending into New Mexico. The similar rocks in Sedona and Holbrook basin are now termed Schnebly Hill Formation (Blakey, 1990; Blakey and Ranney, 2008), although the Corduroy Member of the Holbrook evaporite basin did not extend as far west as Sedona (Figures 1, 2).

Sabkha deposits (moist, playa-like saline basins) characterize the upper Schnebly Hill rocks, as seen in outcrop in Sedona. In time the Pedregosa Sea retreated southeasterly and desert erg conditions existed in northern Arizona and western New Mexico—resulting in Coconino Sandstone deposits. Upper Coconino (called Toroweap at Grand Canyon and Sedona) did not extend this far eastward. A later marine transgression at 270 mya resulted in Kaibab Formation thinning rapidly eastward to as little as 5 m in Chevelon Canyon in the western part of Holbrook Basin and disappearing altogether farther east. Triassic Moenkopi Formation outcrops overlie Coconino Sandstone locally and in turn Chinle Formation in the eastern part of the basin.

Economic interest in the Holbrook Basin centered on petroleum potential during the mid-20th century, until being shown unsuccessful; since then, storage of LPG (liquefied petroleum gas) products within salt caverns started in 1973, and now in the 21st century intense current interest is seen in potash mining (Rauzi, 2008). Additional exploration for uranium is known to have occurred earlier in depressions now considered to be breccia pipes. Topographic expression of the Holbrook Anticline, directly related to evaporite dissolution and collapse, has led to major wind farm development in the 21st Century. With each such interest, new exploration has occurred, revealing more subsurface data regarding the evaporite deposits.

Hydrogeology

The principal aquifer in southern Navajo County is the Coconino Sandstone Formation aquifer (Mann, 1976), but the overlying Kaibab Limestone and the uppermost beds of the underlying Schnebly Hill Formation are hydraulically connected. The Coconino Sandstone is conspicuously cross bedded, is fine- to medium-grained quartz sand, light yellowish gray to tan, and is weakly cemented by quartz, iron oxide, and calcite. It thickens from 120 to 250 m towards the northwest across southern Navajo County, and is about 200 m thick in the vicinity of the Holbrook Anticline.

Recharge of the aquifer results mainly from precipitation and streamflow (Mann, 1976). Most recharge occurs near the Mogollon Rim, some 50 km to the south, where the average precipitation is 50–75 cm/yr. Some recharge also occurs in the vicinity of the Holbrook Anticline by way of precipitation (here averaging 25–35 cm/yr) and piping of surface waters downward through Dry Lake, sinkholes, and other karst features in the area. Ground water flows to the north, towards the Little Colorado River, with a hydraulic gradient of about 6 m/km (30 ft/mi) in the vicinity of the Holbrook Anticline. The Coconino aquifer is unconfined in most of southern Navajo County, but is confined by overlying Moenkopi Formation north of Holbrook and the Little Colorado River (Mann, 1976).

The water table of the Coconino aquifer typically is 120–200 m below land surface in most areas along, or adjacent to, the Holbrook Anticline (Mann, 1976). Therefore, in several areas near the crest of the anticline the Coconino Sandstone is dry, or nearly dry, and the water table is in the uppermost layers of the underlying Schnebly Hill Formation; these strata do not yield much water. The Coconino typically yields 200–2,000 L/min, whereas the Schnebly Hill, along the Holbrook Anticline, yields less than 200 L/min.



Figure 1. Extent of Corduroy evaporite member with overlay of surface areas of karst features referenced in this article.



Figure 2. Principal stratigraphic units associated with evaporite karst in the Holbrook Basin, Arizona. The Corduroy Member of the Schnebly Hill Formation (below Coconino Sandstone and above Hermit Formation) is the principal unit undergoing dissolution. Fault in Precambrian basement and pre-Corduroy Member strata is speculative.

In most of southern Navajo County the quality of water in the Coconino aquifer is good, typically with 200–400 mg/L TDS (total dissolved solids), and the principal constituents are calcium, magnesium, and bicarbonate (Mann, 1976). In the vicinity of the Holbrook Anticline, however, the water is much less desirable, with 500–4,410 mg/L TDS. This water is high in sodium chloride, and is present mainly in the lower part of the aquifer; undoubtedly it is part of the brine formed by dissolution of salt in the immediately underlying Corduroy Member of the Schnebly Hill Formation. A plume of this brine extends northward from the Holbrook Anticline,

flowing in the direction of the hydraulic gradient (Figure 3). This plume is adjacent to the Chimney Canyon subsidence area—only recently recognized as a major evaporite karst area.

Karst activity in the area involves lateral and downward percolation of fresh water through the Coconino aquifer until it encounters the uppermost salt layers in the Corduroy Member, about 215–250 m below the land surface. Salt dissolution is accompanied by development of sinkholes and collapse structures in overlying strata that enhance further flow of fresh water to the dissolution zone. Thus, evaporite karst in this area



Figure 3. Water quality in Coconino aquifer in western part of Holbrook Basin (from Mann, 1976), showing total dissolved solids in mg/L and direction of hydraulic gradient (6 m/km). Holbrook Anticline, McCauley Sinks (X) and Chimney Canyon (CC) subsidence areas are shown.

is self-perpetuating. Depressions and areas of possible breccia pipes conspicuously are near the outer limits of evaporites (Figure 1).

Initiation of Karst Development

Karst development required elevation of the Colorado Plateau, which began during the Late Cretaceous some 75 mya, with intensity increasing during the Neogene combined with northward movement of groundwater downslope from the Mogollon Highlands toward the integrated Colorado River drainage system.

Groundwater moved through the overlying Coconino Sandstone aquifer and began salt removal of the Corduroy evaporite member, continuing to the present. The groundwater encroachment upon evaporite beds and its consequent dissolution is particularly manifested in the southwestern part of the basin; the area of Dry Lake Valley resulted from the collapse of overlying strata into dissolution voids. The area along the Holbrook Anticline includes The Sinks, which contains 250 plus prominent sinkholes, and is perhaps the most conspicuous of karst features expressed in the Holbrook Basin.

The Holbrook Anticline, in fact a monoclinal dissolution flexure, extends northwesterly for more than 100 km from southeast of Snowflake, Arizona, nearly to Winslow, Arizona. Locally the flexure deforms the upper part of the Schnebly Hill Formation and the overlying Coconino Sandstone, Kaibab Formation (limestone), and Moenkopi Formation (Figures 2,4). The flexure produces tension along the top of the fold and compression at the bottom, creating significant open cracks at the top, and buckles at the bottom. The surface expression is locally named the Pink Cliffs, deriving its color from red beds of the Moenkopi Formation.

Originally the structure was referred to as the Holbrook Dome (Darton, 1925), and was once thought to be a combined fault and solution-related feature (Holm, 1938). Bahr (1962) suggested a non-tectonic dissolution origin for the structure and argued that the anticline apparently does not extend below the salt. He believed the structure is a flexure that resulted from dissolution and collapse of a narrow portion of the Mogollon Slope. Doeringsfeld et al. (1958) show this feature is parallel to many low-amplitude folds in the southwestern part of the Colorado Plateau. The persistence of parallel, NW-trending monoclinal structures over large areas of the Plateau (Kelley and Clinton, 1960; Wilson et al., 1960; Davis, 1978) is a compelling statement for structural control of dissolution effects. Peirce et al. (1970) also argued that the surface anticline expression is not seen in the subsurface beneath the salt, suggesting that dissolution played a major role; whether there is basement faulting at depth, as shown by Brown and Lauth (1958), is speculative. The principal sinkhole occurrences are in the Coconino Sandstone, almost exclusively on the steep, southwestern side of the flexure at six distinct locations.



Figure 4. Mechanism of sinkhole collapse along Holbrook Anticline at The Sinks, showing thinning of Corduroy member evaporites in well records (Dean and Johnson, 1989).

The origin and timing of major dissolution and collapse is problematic, but sinkhole formation and collapse are ongoing, as noted previously, and probably began at least by Pliocene time. The uplift and tilting of the Colorado Plateau likely intensified the hydrogeologic environment, but the rates and timing of the orogenic processes are imperfectly known (Lucchitta, 1979). The close association of the dominant regional fractures and the Holbrook Anticline with sinkhole formation is conspicuous throughout the region, but this was not understood by early investigators. Accelerated dissolution of halite during pluvial stages of the Pleistocene seems likely, as intensified hydrogeologic processes are often noted elsewhere in the arid southwest (Smith and Street-Perrott, 1983).

Principal Varieties of Karst Expression The Sinks and Adjacent Areas

The Sinks and adjacent areas are associated with the topographic expression of what has historically been called the Holbrook Anticline—perhaps originally named to foster interest in petroleum exploration. In fact, the ~50 m vertical-relief structural feature in bedrock is monoclinal and now known to result from dissolution of underlying salt beds. Near-orthogonal joint openings in Coconino sandstone follow a NW/NE direction common in this part of the Colorado Plateau (Kelley and Clinton, 1960). At many places along the dissolution monocline are collapse grabens that locally form incipient sinkholes, which may be the primary sinkhole-forming mechanism.

Numerous open fissures and sinkhole-growth patterns coincide with intersecting joints in the Moenkopi and Coconino Formations on the crest of the Holbrook Anticline adjacent to Dry Lake Valley (Figure 5). These fissures are up to 200 m long, 0.3-15 m wide, and as much as 30 m deep. Numerous stories surround these gaping features, some of which purportedly swallowed cattle and possibly two people, and have been described as "bottomless" by local residents. Field observations show that soil is collapsing into joint-fissures at depth, suggesting a similar mechanism for the appearance of piping features in the Dry Lake Valley drainage incidents. The crest and south flank of the Holbrook Anticline are in tension, which explains the open joint-fissures at the surface. Once open, these fissures form a conduit for ground water to penetrate to the relatively shallow (~250 m deep) salt beds below. Near the intersections of some fissure sets, joint-fissures show evidence of subsidence,



Figure 5. Aerial view of The Sinks , looking south down monoclinal flexure toward collapsed Dry Lake Valley (see Fig. 4). Sinkhole locations are strongly influenced by joint openings and collapse grabens in Coconino Sandstone. Nearly 50 sinkholes are shown in this one view, the largest being 100m across.

suggesting how some sinkholes are initiated. The sinkholes occur less than one kilometer to the west and southwest of the monoclinal crest; one of these showed draping and overturning of beds in its collapse. Similar features in the Chimney Canyon area suggest common mechanisms of formation.

A group of 24 sinkholes, termed here "Northwest Sinks," occurs 10 km northwest of the open fissures, along the southwest-dipping crest of the Holbrook Anticline. Two particularly well developed sinkholes are conspicuously larger, deeper, and more regular than the others in this group and they may be younger. The surficial jointing that is so prominent at The Sinks is not nearly as evident here.

Playa Depressions

A series of major depressions and a playa-lake basin, called Dry Lake Valley, cover an area of more than 325 km² in the central and western part of the larger collapse zone. Sinkhole development and collapse are ongoing here, as attested to in local newspaper reports (Snowflake Pioneer, 1984). The artificially impounded Twin Lakes playa (reservoir) in the eastern part of Dry Lake Valley lost more than 6.8 x 10⁵ m³ (550 acre-feet) of water and sediment into open fissures connected to subsurface piping channels. These fissures occurred along a N 53° W trend, generally parallel to the regional structural trend (Sergent et al., 1984). The piping occurred along the reservoir margin during the first filling; presumably the newly formed surface fissures in the playa sediments, which extended for about 1.5 km in a 200-m-wide zone, overlie joint-fissures in Moenkopi redbeds that extend into the dissolution zone of the salt layers. The surfacedrainage features filled with suspended sediment after the water surface dropped 0.6 m, and standing water remained in the surface expression of features within the reservoir (Rucker, personal communication, 1996). The water table in the Coconino aquifer is about 100-120 m below the land surface in Dry Lake Valley (Mann, 1976).

Major drainage incidents occurred at least four times during the 20th century, including nearly 7.4 x 10⁶ m³ (6,000 acre-feet) of industrial wastewater draining into open fissures in the northwest part of Dry Lake in March 1963 (Stone Container, 1991). Multiple clusters of some 40 sinkholes formed in recent lacustrine sediments over an area of about three square kilometers. Nine sinkholes in this group are aligned along a N 44° W trend and some of the others are oriented orthogonally to them. These were still visible in 1996, as subsequent lowering of the reservoir, combined with the arid climate, has effected little erosion since their formation. Loss of water during these drainage events occurs when subaqueous jointfissures sealed with sediment periodically give way to piping, or when new openings form and rapid drainage results. A new sinkhole was observed forming in 1996 at the northwestern edge of the basin at an elevation of 1,780 m; apparently it formed in response to normal runoff rather than lake filling, as the lake levels have been maintained below a threshold level of 1,777 m for many years.

A December 1995 incident of rapid water flow into a piping feature occurred about 13 km south of the Holbrook Anticline (AGRA, 1995) and may have an origin similar to the 1984 fissures. Piping occurred along the downdropped side of a steeply dipping fault oriented N 40° W, apparently through joint/fault intersections (Rucker, personal communication, 1996).

Water flowing into piping channels includes substantial amounts of suspended silt and clay, which in turn seals the fissures and permits more water to accumulate above. Comparison of more recent aerial photos taken in 1977 and 1990 shows new fissures and sinkholes formed in the area adjacent to Highway 377, which crosses Dry Lake Valley; this area was perennially moist in 1996 because of effluent discharge. Local ranchers report draining of stock ponds and playas into piping features at other locations in the valley. According to local reports, the abandonment of Zeniff townsite by Mormon settlers in the early 1900s was prompted in part by the inability to contain irrigation water in Dry and Twin Lakes. Bahr (1962) suggested that all of the Dry Lake Valley area could have formed in this manner, noting numerous sinkhole scars along the base of the Pink Cliffs. The many recent drainage events support his hypothesis.

The linear northeastern shore of Dry Lake is parallel to the regional joint trend and the Holbrook Anticline, suggesting a possible structural control as is seen at many Great Basin playas (Neal, 1969). The origin of playa basins by deep-seated dissolution and gradual surface lowering has parallels in New Mexico and West Texas (Gustafson et al., 1980), but not necessarily on this scale or by the same mechanisms.

Breccia Pipe Structures

The McCauley Sinks are comprised of some 50 individual sinkholes within a 3-km wide depression, grouped in a semi-concentric pattern of three nested rings (Figure 6). The outer ring is an apparent tension zone containing ring fractures. The two inner rings are semi-circular chains of large sinkholes, ranging up to 100 m across and 50 m deep. Several sub-basins within the larger depression show local downwarping and possible incipient sinkholes.

Permian Kaibab Formation limestone is the principal surface lithology—less than 10 m thick and is near its easternmost extent. Although surface rillenkarren are present, and the sinks occur within the limestone outcrops, the Kaibab is a passive rock unit that has



Figure 6. McCauley Sinks, a group of 50 sinkholes in a concentric, nested pattern showing three imperfect rings. The outer and uppermost is a ring fracture; the two inner rings are sinkholes with the innermost at the lowest elevation. A compound breccia pipe origin is suggested for this structure.

collapsed into solution cavities developed in underlying salt beds. Beneath the Kaibab is Coconino Sandstone, which overlies the Permian Schnebly Hill Formation, the unit containing the evaporite rocks—principally halite in the Corduroy Member. The karst in this part of the Holbrook basin is very different from that to the southeast, probably because of the virtual disappearance of the Holbrook Anticline, a structure with major joint systems that help channel water down to the salt beds. McCauley Sinks are also near the edge of the evaporite basin, as are the several other broad depressions of unknown origin. The structure at McCauley Sinks suggests a compound breccia pipe, with multiple sinks contributing to the inward-dipping major depression (Neal and Johnson, 2003).

Richard Lake depression, 5 km southeast of McCauley Sinks, is about 1.6 km wide and with topographic closure of 15-23 m. It is similar in form, but smaller in diameter and contains only a single, central sinkhole. Richard Lake formerly contained water after heavy rains prior to headwater drainage modification but is now dry most of the time. Both are proximate to the adjacent, deeply incised, Chevelon Canyon drainage, but the hydrologic connections are unknown. The larger McCauley Sinks karst depression, along with five other nearby depressions, provides substantial hydrologic catchment. Because of widespread piping into karst features and jointed bedrock at shallow depth, runoff water does not pond easily at the surface. There appears to be much greater recharge efficiency here than in alluvial areas; thus concern exists for groundwater users downgradient from the karst area. A nearby set of pressure ridges trend generally N 30o W, subparallel to the axis of the Holbrook Anticline. In the alluvium at the bottom of the central sinkhole, two secondary piping-drain holes were observed in early 1996. Northwest-trending fissures also were observed on the depression flanks, essentially parallel to the regional structure. Two smaller depressions of lesser dimensions occur in tandem immediately west along a N 620 W azimuth. Secondary sinkholes occur within each of these depressions, as at Richard Lake. Breccia pipes are apt to be found beneath all of these structures.

Blue Mesa Sink is a semicircular collapse feature about one kilometer in diameter just south of the Puerco River within the Petrified Forest National Park (Fig. 1). The depression, with some 15-25 m of topographic closure and with 5-15 degree dip of surface rocks, is similar to that seen in many breccia pipes on the Colorado Plateau, and to the collapse depressions at and near McCauley Sinks. The horst in the depression center is not seen at other breccia pipe structures that overlie evaporites, however; potash thickness beneath the structure may be a developmental factor. The structural framework of this depression may involve concentric ring fractures of unknown attitude. There are no central sinkholes, such as at Richard Lake near McCauley Sinks. The evaporites at shallow depth and similar structure suggest a breccia pipe origin is possible (Colpitts and Neal, 1996), similar to McCauley Sinks and Richard Lake. Other probable solution-induced subsidence depressions occur in the southeastern and northeastern margins of the Holbrook Basin at Ortega Sink, The Crater, Deep Lake, and elsewhere (Peirce and Gerrard, 1966; Harris, 2002).

The geometry of all these depressions bears some resemblance to the San Simon Sink, located above thick Permian salt deposits in the Delaware Basin of southeastern New Mexico. At San Simon, a central sinkhole within a broader depression showed renewed growth and concentric fracturing in 1927, and has been interpreted as a possible breccia pipe being formed (Lambert, 1983). San Simon sink occurs over Capitan Reef, the source of many carbonate karst features at the edge of the evaporite basin (Martinez et al., 1998).

Dissolution of Redwall Limestone beneath these structures in the Holbrook Basin is problematic, but because of the size of these depressions combined with thinner salt in this part of the basin, its involvement is unknown yet seems likely—similar to the many other breccia pipes formed by the Redwall Limestone in the Grand Canyon region.

Chimney Canyon – subsidence depressions

The Chimney Canyon dissolution area includes $\sim 16^+$ km² of karst development and occurs coincidentally along the powerline that extends southwesterly from the Cholla Power Plant at Joseph City. Along the western edge of the karst features is a monoclinal flexure that is smaller but not unlike the "Holbrook Anticline," now recognized as a dissolution monocline. At the crest of the monoclinal flexure are large cracks in the upper Coconino/Moenkopi outcroppings, typical of tensional features in folded rocks (Sanford, 1959; Ramsey,1967). Downdip from the crest are numerous collapse depressions (Figure 7) and buckle folds, typical of karst



Figure 7. Chimney Canyon cracks and depressions in Coconino Sandstone at top of monocline are similar to those near The Sinks, but at an earlier stage of development. Circular-shape sinkholes were not observed.

features and monoclinal folding elsewhere. This area appears less mature than the main Holbrook Anticline structure—created by dissolution of the underlying evaporites. Yet the similarity leads one to suspect a similar origin in groundwater movement toward the Little Colorado River drainage system. The prominent surface manifestation of the Holbrook Anticline seen at The Sinks gradually is less developed progressing northwestward, virtually disappearing at a point that is only about 15 km south of the Chimney Canyon structures. This close association suggests a possible connection of the two collapse and fold belts that is not apparent at the surface.

Surface drainage reversal was noted along several arroyos in the Chimney Canyon drainage, similar to the drainage reversal noticed along Seven Mile Draw at The Sinks to the southeast. Regardless of the uncertainties noted above, it is clear that salt removal and subsidence are ongoing, but perhaps at a slower rate, or more recently than in the thicker part of the salt basin to the southeast.

In early 2012 two anomalous subsidence areas were reported on InSAR data (Conway and Cook, 2013, this volume). A reconnaissance of this area revealed a broad depression similar to those at and around Richard Lake (Neal and Colpitts, 1997). Linear tension cracks were noted along joints in Coconino Sandstone, along with buckle folding near the low point in the depression.

Summary and Conclusions

Evaporite karst is displayed over some 9000 km2 of Permian-age evaporites in the Holbrook Basin, creating a variety of expressions that includes major regional collapse, monoclinal folding, drainage reversal, tensionjoint expansion, buckle folding, graben collapse, sinkholes, and breccias pipes. Well over 600 such features are readily visible on air photos, and many more of smaller scale exist. Karst expression is manifested differently in the western portion of the Holbrook Basin as compared with the east. The west contains substantially more sinkholes, with more mature development and greater relief along the southwestern part of the basin. And whereas individual collapse depressions in the west are of wider dimension and have fewer discrete sinks, they also are present in the east, but to a lesser extent. Surface lithology, alluvial cover, and evaporite thickness combined with groundwater flow create different karst features. The surface conduits through the many areas of karst expression create multiple avenues for potential entry of salt-water brines to aquifers and potential water supplies in downstream communities, requiring continuing vigilance.

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MONITORING EVAPORITE KARST ACTIVITY AND LAND SUBSIDENCE IN THE HOLBROOK BASIN, ARIZONA USING INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR)

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Abstract

The Holbrook Basin located in east-central Arizona is home to more than 500 evaporite-karst depressions. The Arizona Department of Water Resources (ADWR) recently acquired, processed, and interpreted archived Interferometric Synthetic Aperture Radar (InSAR) data to evaluate historical deformation patterns in the Holbrook Basin in preparation for monitoring potential future subsidence related to planned potash mining activities around the Petrified Forest National Park. Three active land subsidence features were identified by ADWR using InSAR data from the European Space Agency's ERS 1 and 2 satellites between 1992 and 1997. Continued subsidence in two of the three features was also identified by ADWR using InSAR data from the Japan Aerospace Exploration Agency's ALOS satellite collected from 2006 to 2011.

In June 2012 Arizona Geological Survey (AZGS) and ADWR staff visited one of the more prominent subsidence features identified using InSAR. Numerous steep-walled evaporite-karst sinkholes were observed en route to the field site. These roughly circular collapse features ranged in size from 40-130 m across and 10-30 m deep. The subsidence features identified through InSAR are much more extensive, up to 1,100 m across; are not as deep, up to 15 m; and do not have steep walls. Local subsidence has resulted in broad closed basins with drainage reversals and numerous expanded joints in the Coconino Sandstone exposed at the surface. A thin sandy soil above the Coconino covers the basin floor except where collapsed into open joints. Expansion along both joint orientations was observed. Which orientation was expanded depended on location relative to ongoing subsidence. Based on field observations and comparison with other collapse features in the region, these three subsidence features are relatively young, constitute

different collapse morphology than nearby sinkholes, and warrant further study. InSAR will remain a critical remote-sensing tool for monitoring land subsidence in the Holbrook Basin.

Introduction

The Holbrook salt basin is located in east-central Arizona and is predominantly composed of halite with lesser amounts of anhydrite, gypsum and sylvite interbedded with dolomite, sand, and shale in the Corduroy Member of the Schnebly Hill Formation of the Permian Sedona Group (Peirce and Gerrard, 1966). The Holbrook salt body underlies more than 9,000 km2 of eastern Arizona between the towns of Winslow, Sanders, Springerville, and Heber. The study area for this report lies southwest of Holbrook and covers approximately 50 km2 (Figure 1). Salt up to 200 m thick has been measured south of the Petrified Forest National Park boundary southeast of Holbrook (Rauzi, 2000). This portion of the Holbrook salt body has become the focus of much interest from investors and mining companies due to the presence of up to 2.5 billion metric tons of potash (sylvite) near the top of the evaporite deposits. Due to the potential for land subsidence related to possible future potash mining, ADWR has begun collecting InSAR data for the region surrounding the limits of the potash deposit. Through evaluation of InSAR interferograms it was determined some areas overlying the Holbrook salt body are actively subsiding today or have been in the last 20 years.

Geologic Setting

The evaporite beds of the Holbrook salt body lie within the upper Sedona Group (Supai elsewhere) and are overlain by Permian Coconino Sandstone, Kaibab Limestone, and fine grained beds of the Triassic Moenkopi Formation. Coconino Sandstone is the most laterally extensive exposed bedrock at the surface throughout the study



Figure 1. Location map of Holbrook Basin, study area extent, and distribution of existing evaporite karst sinks relative to the extent of the Holbrook salt body and anticline.

area. Thin beds of Kaibab Limestone are present near the western boundary of the salt body, but pinch out to the east. Isolated thin exposures of red Moenkopi sands mantle the lighter tan, distinctly crossbedded Coconino Sandstone elsewhere.

Dissolution of salt at depth in the Holbrook Basin has resulted in more than 500 sinkholes, expanded bedrock joints and joint sets, compression ridges and buckles, and numerous subsidence-related geomorphic changes including drainage captures and reversals. The vast majority of sinkhole development is located along the trend of the Holbrook anticline near the southwest margin of the salt body (Figure 1, Neal et al., 1998), but isolated depressions do exist in undeformed beds above evaporite deposits to the northeast. Many of the depressions along the anticline are circular and steep-sided, up to 130 m across and 30 m deep. Depressions located farther from the dissolution flexure are often much more extensive and not as deep, up to 3 km across and 15 m deep. Dissolution of Permian salt and associated subsidence of overlying rock layers in the Holbrook Basin has likely been occurring since the Pliocene (Neal et al., 1998). Using modern remote sensing techniques such as InSAR, land-surface change monitoring, it is possible to determine whether subsidence is ongoing in the Holbrook Basin today.

Land Subsidence Monitoring using InSAR

ADWR has been collecting, processing, and analyzing InSAR data for monitoring land subsidence throughout Arizona since 2002. ADWR's InSAR program has produced invaluable results and end products that are used not only by ADWR but also other state, county, and local agencies, universities, and private companies for their own monitoring, modeling, mitigation, planning and design projects.

Synthetic Aperture Radar (SAR) is a side-looking, active (produces its own illumination) radar-imaging system that transmits a pulsed microwave signal towards the earth and records both the amplitude and phase of the back-scattered signal that returns to the antenna. InSAR is a technique that utilizes interferometric processing that compares the amplitude and phase signals received during successive passes of the SAR platform over a specific geographic area at different times. InSAR techniques, using satellite-based SAR platform data, can be used to produce land- surface deformation products with cmscale vertical resolution. Changes in land elevation are detected through the change in phase of the radar signal. InSAR is used to detect surface motion along active faults, on volcanoes, landslides, sinkholes, and other geologic hazards (Galloway and Hoffmann, 2007).

ADWR has compiled an extensive historical InSAR dataset for the active land subsidence areas identified with InSAR in Arizona. Most data sets cover time periods between 1992 to 2000, 2004 to 2010, 2006 to 2011, and 2010 to present. ADWR has identified more than 25 land subsidence features in Arizona, collectively covering more than 3,600 km².

ADWR has used InSAR not only for monitoring land subsidence but also seasonal deformation (uplift and subsidence), natural and artificial recharge events, as a tool for geological mapping and investigations, locating earth fissures, identifying areas where conditions may exist for future earth fissure formation, and for dam mitigation and land subsidence modeling.

InSAR Results

ADWR collected InSAR data from the Alaska Satellite Facility (ASF) and the Japanese Aerospace Exploration Agency's (JAXA) L-Band Advance Land Observing Satellite (ALOS-1) satellite for the Holbrook Basin in northeastern Arizona. The InSAR data were collected to evaluate land subsidence associated with any of the existing evaporite-karst sinkholes and to develop a baseline for possible future land subsidence related to proposed potash mining near the Petrified Forest National Park.

Six satellite passes of the ALOS-1 path 201 frame 280 SAR data were downloaded from the ASF which allowed ADWR to create fifteen different interferograms. Two new land subsidence features were identified using the ALOS-1 InSAR data (Figure 2).

Land subsidence measured with the ALOS-1 InSAR data from 12/06/2006 to 02/01/2011 in the western and eastern sink was as high as 5 cm and 26 cm, respectively. This interferogram covering 4.15 years was the longest timespan available to be processed for the ALOS-1 InSAR pairs. The spatial extent and magnitude of land subsidence of the new land subsidence features was consistent across all the other interferograms.

To better understand the historical activity of the new land subsidence features, ADWR ordered archived SAR data for the European Space Agency's (ESA) European Remote Sensing-1 and 2 (ERS-1and ERS-2) satellites.

A total of 28 satellite passes of ERS-1 and ERS-2 track 456 were downloaded from ESA which allowed ADWR to create 27 interferograms. The historical dataset from 1992 to 1997 identified the same two land subsidence features identified in ALOS-1 dataset. The ERS-1 and ERS-2 dataset also identified a third new subsidence feature



Figure 2. ALOS-1 12/06/2006 to 02/01/2011 Interferogram.







Figure 4. ERS-1/2 11/24/1992 to 03/07/1997 Interferogram.

located approximately 5 km north of the eastern feature. This feature was not observed in the more recent ALOS-1 dataset (Figure 2).

The reasons why the northern land subsidence feature is apparent in the 1992-1997 interferogram, but absent in later years (2006-2011) are unknown. It is possible subsidence at the northern feature is episodic or complete. Land subsidence as high as 2.7 cm, 3.5 cm, and 1.7 cm was measured with the ERS-1 and ERS-2 InSAR data in the western, eastern, and northern subsidence features, respectively. Continued InSAR monitoring of this area will help constrain subsidence rates and patterns.



Figure 5. Example of a compression ridge within the eastern subsidence feature. Broken bedrock along this ridge follows a sinuous east-west trend. Bedrock slabs in the background are pushed against and above one another.



Figure 6. Example of an expanded joint within the eastern subsidence feature.

Active Sink Morphology

The thickness of salt below the western and northern subsidence features is approximately 30 m at a depth of approximately 240 m and 225 m, respectively. Salt below the eastern subsidence feature is between 30



Figure 7. Subsidence-related geomorphic features of the eastern active sink. Aerial imagery from 2010 National Agricultural Imagery Program (NAIP).

and 60 m thick at a depth of 245 m. For comparison, salt below the greatest concentration of evaporitekarst features along the Holbrook anticline is between 60 and 90 m thick at a depth of approximately 230 m (Rauzi, 2000). The eastern sink was visited in the field and subsidence-induced geomorphic features such as drainage reversals, closed-basin formation, compression ridges, and expanded joints were observed (Figure 7).

The overall shape of the eastern sink is that of a broad depression with gently sloping sides that gradually rise to meet undeformed subtly northeast-dipping beds of Coconino and Moenkopi sandstone outside the InSAR signature. While no vertical walls or steep sides are present at the eastern sink as observed in more mature, inactive sinks nearer the Holbrook anticline, the deepest portion of the eastern sink near the southern portion of InSAR signature is adjacent to a distinct Coconino Sandstone slope with many expanded joints. Similar exposures exist near the northern and northwestern limits of the actively subsiding sink. The depth of the eastern sink reaches a maximum of approximately 13 m relative to the top of surrounding sandstone slopes which is dramatically less than depths observed at many mature, inactive sinks to the west.

Drainages near the southern limit of the eastern sink terminate in a fine-grained, sediment-filled bowl

surrounded by juniper and small shrubs. Slabs of broken Coconino Sandstone litter the slopes. Portions of drainages in the subsiding area that previously flowed northeast now flow southwest into the closed depression. No water was present in the lowest point during any of our field visits, so it is unknown whether standing water develops or flow infiltrates immediately during heavy runoff events.

No standing-water lines or flotsam rings were observed. Rills, bar and swale channel deposits, and plant matter suspended in and around trees near channels indicate at least moderate overland flow has occurred recently in channels leading to the lowest point of the sink.

Fine-grained reddish sand, presumably reworked from nearby Moenkopi outcrops, mantles much of the side slopes and bottom of the active sink. Occasionally this nearly continuous cover is broken by collapse of the overlying sediment into an open joint below (Figure 6). These open joints are typically 20-30 cm wide and up to several meters deep. Joint width tapers with increasing depth, and the bottoms of open joints are filled with red sand that has fallen in from above. Linear depressions in surface sands often parallel or lead to exposed joints. There are likely many more open joints in the shallow subsurface that are presently obscured or plugged by overlying sand. Areas of exposed bedrock within the subsidence feature exhibit broken rock along expanded joints and are generally open to greater depths than those mantled by sediment. The Coconino Sandstone has two joint orientations that are alternately expanded depending on orientation relative to tension from ongoing subsidence. In some locations within the subsiding area joint orientations are alternately expanded resulting in a zig-zag openjoint set appearance. Exposed Coconino Sandstone at the northern and northwestern edge of the InSAR signature exhibits wide expansion joints up to 1 m across, up to 10 m deep, with vertical offset up to 1 m between blocks. Successive vertical offset across open joints has resulted in a topographic slope defining the edge of the active subsidence feature. Coconino outcrops beyond these exposures do not exhibit this deformation. The presence of wide expansion joints with vertical offset just beyond the limits of modern subsidence indicates subsidence may have initiated somewhat farther to the north than indicated by recent InSAR data (Figure 7).

Expansion of joints farther upslope in the subsidence feature results in compression between subsiding blocks lower in the landscape. Compressional ridges have been observed at other subsidence locales in the Holbrook Basin such as the McCauley Sinks, Richard Lake, and at the base of the Holbrook anticline (Neal et al., 1998). The ridges observed here are somewhat smaller than those described by Neal and others but some appear freshly broken, exhibiting jagged broken sandstone shards and slabs of rock precariously balanced against one another (Figure 5). The ridges observed in the eastern active sink are 1-2 m tall, several meters wide, and up to 200 m long. The ridges trend roughly east-west and are more abundant in the northern portion of the subsidence feature immediately downslope from the cluster of wide expanded joints with vertical offset at the northern limit of modern subsidence.

InSAR Methodology

The ALOS-1 and ERS-1/ERS-2 satellites that were used for the InSAR analysis of the Holbrook Basin utilize sensors of different wavelengths, L-band and C-band, respectively. L-band has a wavelength of approximately 23 cm while C-band has a wavelength of 5.6 cm. Both sensors are processed using the same interferometric methodology.

Interferometry is used to process the change in phase between each pair of satellite data. It is important to note the C-band and L-band InSAR datasets cannot be processed together due to the different sensors. InSAR processing also requires a digital-elevation model (DEM) to remove the topography from the phase component of the radar signal. A 30 m DEM from the United States Geological Survey National Map Viewer website (<u>http://viewer.nationalmap.gov/viewer/</u>) was used to remove the topographic phase component.

Both the L-band and C-band interferograms (Figures 2-4) were unwrapped using a color wrap of 1/2 of each sensor's wavelength. When examining the different interferograms, one complete color cycle (blue-red-yellow-green-blue) represents 2.8 cm of deformation for C-band and 12 cm for L-band. The color bands can be viewed as deformation contours when examining each feature. ADWR recently started collecting regularly scheduled InSAR data (Figure 8) for the Holbrook Basin using the Radarsat-2 C-band satellite. These new InSAR data will provide ADWR with a critical tool for

monitoring ongoing land subsidence at these two new sinks as well as possible land subsidence associated with planned potash mining around the Petrified Forest National Park.

Conclusions

Evaporite-karst processes in the Holbrook Basin have created a dynamic, geomorphically intriguing landscape. With recent interest in potash mining and continued storage of liquefied petroleum gas in the same salt body that is the source of dissolution beneath hundreds of nearby evaporite-karst features, understanding modern subsidence rates and mechanisms is important. Because the vast majority of existing evaporite-karst features in the Holbrook Basin are no longer subsiding today, the opportunity to observe the gradual processes that lead to sinkhole formation is an exciting prospect.

In addition to continued subsidence monitoring with InSAR, we have begun collecting repeat field observations, photos, and have installed eye bolts across expanded joints near the edges of the subsidence feature to enable repeat measurement in the future. A benchmark near the most rapidly subsiding area within the eastern sink was installed and static GPS measurements were obtained to supplement future InSAR data and enable repeat surveying of subsidence within the feature. In an attempt to better understand the subsurface geometry



Figure 8. Radarsat-2 InSAR frame used to monitor future land subsidence in the Holbrook Basin.

and lithologic structure deep Refraction Microtremor (ReMi) and electrical-resistivity measurements were conducted both within and outside the subsidence feature. Results of this investigation are pending and future visits to the eastern subsidence feature to collect tensiometer measurements are planned. In addition, field visits to other nearby active-subsidence features, as well as Richard Lake which most closely resembles the extent and morphology of the eastern active sink, are proposed.

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GEOPHYSICAL INVESTIGATIONS OF THE EDWARDS-TRINITY AQUIFER SYSTEM AT MULTIPLE SCALES: INTERPRETING AIRBORNE AND DIRECT-CURRENT RESISTIVITY IN KARST

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Abstract

Electrical electromagnetic geophysical and characterization is a proven tool for delineating obscured subterranean karstic features, such as caves, sinkholes, and solution enlarged fissures. Geophysical characterizations allow a wide range of deployment scales; airborne methods can accommodate a regional view on the order of kilometers, and ground-based methods can follow up with focused data on the order of meters. A helicopter frequency domain electro-magnetic (HFDEM) survey and ground-based direct-current electrical resistivity imaging (DC-ERI) geophysical studies at the Camp Bullis Military Training Site (Camp Bullis) in central Texas have been used to characterize permeability properties of the Edwards and Trinity Aquifers in the area. Results of three separate investigations identified zones of high density karst features and characterized specific karstic voids, including caves. In 2003, the USGS completed an HFDEM survey of Camp Bullis and nearby areas to map and image subsurface features related to the groundwater resources. The survey refined locations of mapped and previously unmapped faults and characterized the heterogeneity of the subsurface electrical signature. Karst mapping at Camp Bullis identified over 1500 features, and high density zones of features correspond with areas of high resistivity from the HEM data. DC-ERI surveys at several locations were used to infer and characterize known and hypothesized karst features. Site 8 suggests an inferred fault and

dissolution feature. Two other sites were surveyed near major caves that directly recharge the Trinity Aquifer (indirectly to Edwards Aquifer) along Cibolo Creek. Integration of multi-scale geophysical datasets could be used to augment aquifer-wide recharge characterization and quantification.

Introduction

The Edwards and Trinity Aquifers are critical water resources, supplying high-quality potable water to over two million people in the greater Austin-San Antonio region of central Texas, USA. These carbonate aquifers are structurally juxtaposed by extensive Miocene tectonic deformation associated with the Balcones fault zone, where the younger Edwards Group has been downthrown relative to the older Trinity Group. These karstic aquifers are managed separately by regional water regulatory entities, and have been historically treated as independent systems, both scientifically and from a water policy standpoint.

Three separate electrical geophysical investigations at Camp Bullis Military Training Site (Camp Bullis) (Figure 1) were performed to characterize the hydrogeologic properties of this 113 km² (28,000 acre) area that includes both Edwards and Trinity Group outcrops. In 2003, the U.S. Geological Survey completed a helicopter frequency domain electro-magnetic (HFDEM) survey of Camp Bullis and nearby areas to map and image



Figure 1. Location of Camp Bullis lies within the Edwards and Trinity aquifers (Zara, 2011).

subsurface features related to groundwater resources. DC-ERI surveys at several locations have been used to infer and characterize known and hypothesized karst features and structural features. One of these sites, located near a heavily investigated remediation area (Site 8; Figure 4) possibly indicates an inferred fault and dissolution feature. Two other sites were surveyed near major caves that directly recharge the aquifers along Cibolo Creek on the north side of Camp Bullis with mixed geophysical results. The HFDEM data provide a regional-scale survey of Camp Bullis and the surrounding area and are complemented with two site specific DC-ERI surveys that provide more details of localized electrical resistivity properties related to dissolution features.

Hydrogeologic Setting

The hydrogeologic setting of Camp Bullis has been documented in numerous reports related to the Edwards and Trinity Aquifers, both formed in Cretaceous limestones. Two publications in particular focused directly on the surface geology (Clark, 2003) and structure of the bedrock (Ferrill et al., 2003). The Edwards Group (Kainer Formation) covers the southern third of Camp Bullis. The USGS published a lithologic description of the Edwards in Bexar County (Stein and Ozuna, 1995). The Glen Rose Limestone covers the northern two-thirds and most of the subsurface of Camp Bullis. It is divided into two members. The upper member has been divided into five hydrogeologic intervals, previously designated A through E (Clark, 2003), but the intervals were formalized with names by Clark et al. (2009). Figure 2 shows a three dimensional block diagram of Camp Bullis (Zara, 2011).

The cavernous member (interval A) is formed by alternating and interfingering mudstone, wackestone and packstone and is well karstified. It overlies the Camp Bullis member (interval B), which is lithologically similar to the cavernous member, but has less karst development and lower permeability. The upper evaporite member (interval C) is a thin layer of highly soluble carbonates and evaporites, characterized by breccia porosity, boxwork permeability and collapse structures. The fossiliferous member (interval D) has low porosity and permeability, with the exception of a caprinid biostrome near the top of the interval, which is well karstified. This biostrome is thickest in the center of Camp Bullis, and thins to the north. The lower evaporite member (interval E) is quite similar to the upper evaporate member (interval C), with mostly dissolved evaporites diverting groundwater horizontally. The lower member of the Glen Rose Limestone is composed primarily of massive, fossiliferous limestone and is well karstified with significant recharge features (fractures, faults, and caves that rapidly transmit surface water to the aquifer) along Cibolo Creek.

The area in and around Camp Bullis has been extensively karstified, fractured, and faulted, both in the Kainer Formation (Edwards Group) and Glen Rose Formation (Trinity Group). Detailed surveys were conducted over many years, documenting over 1500 karst features (Zara, 2011). Karst feature density was estimated using karst feature locations and the weighted karst significance values (0-720), as quantified by Zara and Veni (2010). Features' significance numbers were determined by giving numerical values to each karst feature, using hydrogeoloigcal characteristics proportional to potential recharge. Results are shown in Figure 3, with darker areas indicating higher karst density and significance. These data are correlated with results of geophysical studies.



Figure 2. Block Model of Camp Bullis based on Clark (2003) and Ferrill et al. (2003). Mapped karst features are shown as orange points. Figure modified from Zara, 2011.

Geophysical Investigations

Three independent geophysical investigations are shown here to display different scales of data collected at Camp Bullis. Locations of all the studies are shown in Figure 4, including the HFDEM surveys, the Site 8 DC-ERI remediation survey, and two DC-ERI surveys along Cibolo Creek to the north (Jabbas Giant Sink and Bullis Hole).

Airborne Electromagnetic Survey

A HFDEM survey was flown over a portion of northern Bexar County covering the Edwards Aquifer Recharge Zone and the Trinity Aquifer at Camp Bullis, Camp Stanley Storage Activity (adjacent to Camp Bullis on the west), and part of Cibolo Creek east of Camp Bullis (Figure 4). The HFDEM survey used the RESOLVE[®] system flown by Fugro Airborne Surveys, which uses



Figure 3. Karst feature density map of Camp Bullis showing the spatial distribution and significance number of karst features (Zara, 2011).



Figure 4. HFDEM survey data at 115 kHz frequency from Camp Bullis. DC-ERI sites are shown as white circles. The Edwards-Trinity contrast is clearly shown in the HFDEM data (Smith et al, 2005) The water table is 30+ meters below the land surface throughout Camp Bullis, thus these resistivity values reflect the vadose zone.

five horizontalcoplanar coils and one vertical coaxial coil for electro-magnetic field measurements. The six frequencies ranged from 400 Hz to 115,000 Hz. Details of the survey specification and digital data aredescribed by Smith et al. (2005). The survey was flown with east-west flight lines and a nominal line spacing of 200 m with a sensor elevation of 30 m except as required for safety considerations and FAA regulations. In-fill lines were flown in the central part of the survey area to yield an effective flight line spacing of 100 m. The measured electromagnetic fields were converted to apparent resistivity by the contractor for each frequency. The depth of penetration increases with decreasing frequency and with increasing resistivity. The shallowest depth of penetration is for 115,000 Hz which averaged 7 meters for all of the survey. The apparent resistivity is shown in Figure 4.

The survey refined locations of mapped, located previously unmapped faults, and characterized the heterogeneity of the subsurface electrical signature. In general, the massive limestones of the Edwards Recharge Zone at the southern end of the survey are shown as an area of very high apparent resistivity (100s of Ω -m in the HFDEM survey). The sharp NE trending boundary between the high resistivity on the south and more moderate apparent resistivity to the north reflects a normal fault boundary between the Edwards and Trinity Aquifers. The Trinity Aquifer is characterized
by alternating mudstones, siltstones (low resisitivities; cooler colors in Figure 4), and limestones (warmer colors) which give the aquifer a variable signature. In general the upper part of the Trinity Aquifer is composed of thin discrete limestone and siltstone layers that give the variegated color pattern in Figure 4. The middle Trinity is composed of more massive reefal structures within mudstone units.

The trends in the apparent resistivity map correlate to and augment the mapped geology. The HFDEM map shows greater detail in the lithologic changes than indicated in geologic maps such as the thin limestone units and more detail in structural trends. There is also a strong correlation of the occurrence of karst features (Figure 3) with the HFDEM map, suggesting that the geophysical data may also reflect values of high resistivity that would be significant if large volumes of air-filled voids (very high resistivity) exist in the subsurface.

Site 8 DC-ERI

A surface-based electrical resistivity survey was conducted south of the Site 8 Landfill to map the structure of the top 50 m of the exposed Glen Rose limestone. The landfill is located approximately in the center of Camp Bullis, to the west of Lewis Creek (Figure 5A). The purpose of the resistivity survey was to gain a better understanding of potential karst features that would help explain contaminant transport through the underlying aquifer. Contaminants were detected in a number of wells down gradient of the site, just south of the area shown in Figure 5.

The resistivity data were acquired along 16 transects spaced approximately 6 m apart. The pole-pole array was used for acquisition, with remote electrodes placed at least 700 m away. Transects were about 95 m long with 3m electrode spacing and data were collected with a SuperSting R8. The pole-pole array is known to provide rapid acquisition with high signal to noise ratio and deep imaging. However, the array also has the lowest resolution and therefore not optimal for locating small scale features that would provide the best insight into the range of sinkhole sizes. To accommodate a higher resolution, the pole-pole data were converted to an optimized four-pole array that included external dipoles (similar to the dipole-dipole array), internal dipoles (Schlumberger array), and overlapping dipoles according to the procedure outlined in Loke et al. (2010). The conversion of two-pole to four-pole data was conducted through superposition (Rucker, 2012).

Although the data were collected along 2D transects, the spacing between lines allowed the domain to be modeled in three dimensions, to a depth of 45 m below ground surface. RES3DINVx64 was used to inverse model the data and was opted for additional diagonal smoothing to reduce striping inherent in modeling volumes comprised of individual transects. The results of the resistivity distribution are shown in Figure 5B as an overhead view of two resistivity isopleths: $250 \ \Omega$ -m s a transparent lighter blue and $400 \ \Omega$ -m as a darker opaque blue (which can be observed through the lighter transparent blue in the northwestern portion of the site).

Values lower than 250 Ω -m have been removed making those areas devoid of color, i.e., the lowest values have been blanked. Based on the vertical distribution of resistivity, the figure highlights the resistivity values in the upper 11 m of the domain. Below 11 m, the resistivity values are less than 250 Ω -m, likely due to the influence of increased saturation.

The results show that there is an overall trend of high resistivity features that align along an approximate N22E strike to the northeast. A clear banding of the highest values can be observed through the center of the site, which likely represents more competent limestone. The low resistivity material that has been removed from the image is hypothesized to be soil-filled buried sinkholes with higher clayey material and moisture content. Unfortunately, wells drilled in the immediate vicinity of the study did not uncover evidence of sinkholes, as they were placed prior to resistivity acquisition. The sinkholes appear to also align at N22E or perpendicular at N58W. Arrows have been provided to highlight these directions. The spatial density of low resistivity material increases in size and number towards the east (closer to Lewis Creek). Given this information, two possible scenarios of contaminant transport emerge. Either the sinkholes provide a means of recharge from landfill runoff, or possibly the underlying landfill liner (if one existed) integrity has been breached through further sinkhole development.

Cibolo Creek Karst Features

Two field DC-ERI surveys focused on imaging known air-filled karst features located within the floodplain of



Figure 5. (A) Study area of surface resistivity south of the Site 8 Landfill showing the survey lines. (B) Overhead view of three dimensional resistivity showing two isopleths: 250 (light blue) and 400 Ω -m (dark blue). Values less than 250 Ω -m were removed to highlight patterns of potential sinkholes filled with soil. The medium blue is from the combined effect of both blues. Electrodes are black dots.

Cibolo Creek at the northern border of Camp Bullis. The two target features were Bullis Hole and Jabba's Giant Sink. Both have cave entrances located on the creek bluff and are mapped to extend below Cibolo Creek (Zara and Veni, 2010).

Two creek-parallel, cave-perpendicular 2D ER lines were recorded at Bullis Hole (Figure 6). The first line ran across sinkholes associated with the cave entrance, and the second line was 30 m northeast of the first line, beyond where Bullis Hole was mapped (Figure 7). At Jabba's Giant Sink (Figure 8), two nearly perpendicular 2D ER lines crossed over the cave location (Figure 9). Electrode spacing ranged from 1.5 to 5 m, depending on the depth required for imaging the karst features and the available space. Dipole-dipole and Schlumberger datasets were collected and merged prior to inversion for each line. Line topography was recorded with a total station and included in the inversion. The merged datasets were inverted in RES2DINVx64 with a robust model constraint.

The ER line running over the Bullis Hole sinkhole captured the subsurface expression of the cave (Figure 7). The main collapse area was noted at location 72-73 m along Line 1 and coincides with a small high resistivity (> 250 Ω -m) anomaly within 1 m of the surface. A more notable high resistivity feature was imaged adjacent to the sinkhole (66-69 m) that extended to 5 m depth, which was interpreted to represent the shallow passage of Bullis Hole just offset from the ER line where both the depth (~2 m) and size of the cavity agree between the ER and cave map. Uncertainty in the imaged feature's dimensions result from the threedimensionality of electrical properties in the subsurface that are modeled in 2D, and the ER inversion process inherently smooths discrete and abrupt ER features and boundaries (Day-Lewis et al. 2005). The Line 2 inversions did not resolve any apparent karst features.

Jabba's Giant Sink extends under Cibolo Creek and was imaged well by the ER surveys (Figure 9). In Line 1, a highly resistive feature (> 300 Ω -m) was imaged at the cavern depth (10 m) at the correct position along the line (~75 m). The extension of the high ER values at the same depth suggest some lateral extension (54-99 m) of voids in the subsurface, as near equal horizontal and vertical smoothing (averaging) was used during the inversion. Line 2 intersected Line 1 near the projection



Figure 6. Cave map shows Bullis Hole cave, which is located on the right bank (south) of Cibolo Creek. This cave extends below the creek bed (Zara and Veni, 2010).



Figure 7. ER results at Bullis Hole cave. Line 1 imaged a high ER area where the cave crossed the line (~70 m). The second line did not reveal any new potential karst voids.

of Jabba's Giant Sink, and high resistivity values (> 200 Ω -m) between 33-42 m on Line 2 were centered on the expected cave depth (~10-12 m). A thin resistive anomaly further down the line (50-52 m) at 5 m depth may represent a small cavity.

Discussion

In this paper, we evaluated three geophysical case studies performed at Camp Bullis. They were each conducted independently from one another with different specific objectives and a range of scales. The HFDEM survey utilized regional-scale methodology to capture the subsurface electrical properties of the geology beneath Camp Bullis and surrounding areas. The Site 8 investigation imaged the geophysical signature near a contaminant remediation site, characterizing variable zones of resistivity, relating to possible locations of karstic features. DC-ERI surveys along Cibolo Creek directly targeted known, mapped caves below the creek bed, and these caves have been observed to discretely recharge into the aquifer. A next step would be to link these disparate studies with other known hydrogeologic, hydrologic, and geomorphic data to improve the

understanding of recharge heterogeneity across the aquifer system. To accomplish this at Camp Bullis, we would utilize HFDEM data as the common data set.

Comparison of the HFDEM data (Figure 4) with the mapped geology (Figure 2) indicates the electrical properties imaged closely relate with the different hydrogeologic properties of different formations and members of the Edwards-Trinity carbonate rocks. The primary porosity heterogeneity is one component of the permeability signature, and quantified with the electrical resistivity data. This is most clearly observed is where the Kainer Formation (Edwards Group) has been juxtaposed through normal faulting adjacent to the upper members of the Glen Rose Formation (Trinity) in the southeast section of Camp Bullis. The differences in primary porosity between these two formations are substantial, and are clearly reflected in the HFDEM data. Other members within the Glen Rose also show substantial electrical variation, and relate to increased porosity and varied lithology associated with reefal depositional environment of the Lower Glen Rose along Cibolo Creek.



Figure 8. Cave map of Jabba's Giant Sink cave, located on the right bank (south) of Cibolo Creek. The cave extends below the creek bed and has been observed to rapidly recharge the aquifer through an active whirlpool during floods (Zara and Veni, 2010).



Figure 9. ER results at Jabba's Giant Sink (cave outline shown in orange). Both lines 1 and 2 resolve high ER features where the cave was expected to cross into the surveys (\sim 75 m – line 1; \sim 40 m – line 2). Line 2 may have resolved a shallower cavity (\sim 50 m).

Secondary permeability is reflected in the faulting and subsequent karstification of the Edwards and Trinity aquifers in this region of central Texas, and is one of the major factors that make the Edwards Aquifer is such a prolific water source. Camp Bullis has been meticulously surveyed for karst features, possibly in greater detail than any other large, contiguous area in the U.S. This rich dataset (Zara, 2010) provides a unique opportunity to compare known, evaluated karst features with the regional electrical properties (Figures 3 and 4). Areas of high resistivity in the HFDEM data have a significant correlation with zones of high density karst features. This can be expected, since air-filled karstic voids have a significant effect on the electrical signature. This is shown on the local scale by the other two DC-ERI surveys conducted on Camp Bullis. They were conducted in areas of moderate to high resistivity in the HFDEM data, and show that voids do have a significant impact on the electrical properties in the study area. The likely resultant HFDEM data set likely reflects both increased primary porosity in the matrix rocks and enhanced secondary porosity in the faults, fractures, solutional voids, and karst conduit networks. This electrical reflection of the permeability structure of the Edwards-Trinity aquifer system of the HFDEM data could be a significant tool applied throughout the region to improve our understanding of the spatial heterogeneity of aquifer recharge.

Conclusion

Three different electrical geophysical studies performed at Camp Bullis were evaluated for their characterization of the permeability fabric of the Edwards and Trinity aquifers in central Texas. HFDEM data of the entire study area closely correlate with mapped geologic outcrops and spatial distribution of karst features. Localized DC-ERI investigations at two settings correspond to electrical signatures (high resistivity zones) of the HFDEM data, and show the applicability of potentially identifying karstic voids, or areas with more secondary karstification. The unique, extensive hydrogeologic data that exists for Camp Bullis can be expressed in the electrical signature of the subsurface, and quantified on a large scale by HFDEM datasets. Applying this methodology throughout the region to improve quantification of recharge could significantly increase the ability of regional groundwater models to simulate aquifer dynamics of the Edwards and Trinity aquifers and their interaction with each other.

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SUBBOTTOM PROFILING INVESTIGATION OF SINKHOLE LAKE STRUCTURE IN BAY AND WASHINGTON COUNTIES, FLORIDA

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Abstract

The sandhill lakes of Bay and Washington Counties, Florida, are deep, pristine environments which owe their existence to sinkhole activity as observed in limited bathymetric maps and in the appearance of small circular depressions around their perimeters ("string of pearls") observed on aerial photography especially during low water level periods. However, little investigative information exists that shows the internal, deep structure of these lakes and how that structure might affect interaction with groundwater flow and lake levels.

High resolution seismic reflection surveying with a marine subbottom profiler (SBP) was applied over reconnaissance profile lines on a series of these sandhill lakes in order to investigate the deep structures of the lakes for purposes of determining the mode of sinkhole development within each lake and their relationships with subjacent aquifers, specifically the Floridan aquifer system (FAS). The SBP provided mapping of the bathymetry (maximum 15 - 32 m water depth) and subbottom structure up to an additional 18 - 24 m below the bottom, all with a theoretical resolution of approximately 0.10 m bed thickness.

The resulting SBP profiles showed that a) the lakes form through the coalescence of numerous small sinkhole features, b) the sinkhole features penetrate the uppermost FAS, disrupting the overlying sediments, and c) multiple stages of sinkhole development and sediment movement are exhibited in the subbottom strata.

Introduction

The sandhill lakes region (Figure 1) of the Florida Panhandle occupies portions of Washington and Bay Counties (north of Panama City), Florida. It is a region of some 200 crystal-clear lakes that owe their existence to sinkhole activity. The lakes are often circular in plan with a striking blue color owing to low nutrient levels and pure white sugarsand bottoms, and their internally drained basins are the homes of many endangered or threatened floral and faunal species, including bald eagles, gopher tortoises, smoothbark St. John's wort, and several species of carnivorous sundews.

It has long been common knowledge that the lakes have sinkhole origins (Grubbs, et al., 1995; Pratt, et al., 1996), but after viewing shorelines during periods of drought when lake levels drop, it was suspected that the mode of creation and growth was complex as demonstrated by the "string of pearls" appearance of new, smaller depressions forming around the perimeter of the lakes (Figure 2). In addition, there were questions regarding the interaction and connection between the lakes, the underlying surficial (unconfined) aquifer, and the deep, semi-confined Florida aquifer system (FAS). As a means of developing an understanding of lake structure and growth mechanisms as well as an understanding of the interconnection between the lakes and the FAS, a program of marine (lake) geophysical imaging was conducted in five sandhill lakes in the region. The method applied is high resolution seismic reflection profiling or sub-bottom profiling.



Figure 1. Plan view of sandhill lakes of NW Florida.



Figure 2. Aerial photograph of a sandhill lake showing a "string of pearls" of new, recent sinkholes along the lake shore.

SBP Geophysical Methodology

The acoustic sub-bottom profiler (SBP) is a geophysical technology that measures the depth of water as well as thickness and structure of sub-bottom sediments using acoustic echo sounding principles. The technology is quite similar to simple depth gauges/fish finders found on boats. The principal difference is that the SBP employs an acoustic source that has increased signal power and somewhat lower frequency than a common depth finder. This allows for some penetration into the bottom sediments. Reflections of the acoustic signals from the sediment layers may also be detected as the boat cruises along a lake-crossing profile (Tihansky, et al., 1996; Reich, et al., 2012).

SDII employed the Syqwest StrataBox SBP system consisting of a processor/controller circuit box, an acoustic piezoelectric source (10,000 Hz center frequency), and an auxiliary satellite GPS system - all controlled by a laptop computer. The system is battery powered, and instrument specifications quote water penetration depths up to 150 meters (490 feet) and up to 40 meters (130 feet) of sub-bottom penetration under ideal conditions. With an assumed seismic compression wave velocity of 1,500 m/sec for the water and saturated sediments, the 10,000 Hz source can realize resolution of beds on the order of one wavelength or less (approximately 0.10 meter). Figure 3 shows the boat used with the transducer in the water just below the GPS antenna.

Operationally, the acoustic source is lowered below the water surface to ensure excellent coupling of the acoustic waves into the water column. The source is directed downwards to scan below the boat. Communications are established between the computer and the GPS system so that positional coordinates can be recorded concurrently with the acoustic echoes. Parameters (e.g. maximum depth range, instrument gains) are optimized for a given lake, and a digital file is opened. The boat is piloted on a straight-line course across the lake, and the depth-converted cross-section is displayed in real time during the crossing. Figure 4 is a representative SBP cross-section acquired on one of the lakes in the study area. The only post-acquisition processing (besides printing) of these data sets was a mute to remove reflections from within the water column caused by vegetative masses and fish.

The following principal features can be seen in the example cross section in Figure 4 and in other cross sections included here.

- Time zero (the water surface, 0 meters depth) is represented by the horizontal line across the top of the section.
- The total horizontal length of the section is labeled at the top of the section. Actual position coordinates of any point along the cross-section can be determined by playing back the SBP file through the acquisition program and using a cursor to determine GPS coordinates at any specific point of interest.
- The vertical scale is depth in meters. For the sandhill lakes project, we used a maximum depth range of 0-36.5 meters (0-120 feet).
- The primary reflection from the bottom of the lake is the bright reflection interface indicated as "primary (bottom) reflection" on Figure 4. This



Figure 3. Photograph of SYQWEST SBP system mounted on an aluminum boat.



Figure 4. Example SBP section.

represents an acoustic wave that traveled down to the lake bottom and reflected back up to the boat (down plus up path).

- The secondary reflections labeled as "multiples" are primary reflections that have reflected back downwards from the water surface and represent second, third, fourth, etc. roundtrips of the signal. Multiple reflections become a noise issue when water depth is shallow, but as depth increases the multiples begin to disappear off the bottom of the profile because the round trip time is double, triple, etc. that of a primary reflection.
- Between the primary bottom reflection and the first multiple, we see clear reflections from subbottom sediment layers.

SBP Results ("Big Blue Lake")

Big Blue Lake was the largest of the five lakes profiled. The lake is approximately 230 hectares in size (2,300 m by 1,000 m). A total of nine profiles were acquired as shown on Figure 5. In this manuscript, we present the results of two specific profiles, BB-3 and BB-4.

Profile BB-3 is approximately 2,027 meters long running down the long axis of Big Blue Lake from north to south (Figure 5). Profile BB-4 is a shorter (945-meter) profile extending from southeast to northwest along the southern shore of Big Blue Lake. This profile extended over some smaller circular depressions observed on historical air photographs taken when lake levels were lower.

Data were acquired over a two-day period due to heavy afternoon thundershowers typical of this region in the summer months. All geophysical activities are curtailed at the first sign of lightning.

Profile BB-3 – Big Blue Lake

Figure 6 presents the SBP image acquired along Profile BB-3. There is significant vertical exaggeration on this

profile as it represents a very long profile. The main feature displayed on this profile is the lake bottom bathymetry varying between 4.5 and 22.9 meters water depth. This vertical exaggeration emphasizes the features that indicate that Big Blue Lake has *not* formed as the result of a central, conical depression related to a single sinkhole throat. From the image, we see that along this profile there are at least six discrete sinkhole structures, and some of these are well developed (i.e., they are deep with steep sides) while others appear to be just starting to depress the lake bottom. The deepest depression on this profile shows evidence of slumping.

Note in Figure 6 that the depressions have a common depth, which is at or below the depth of the semiconfining strata that separate the surficial aquifer and the FAS. The small sediment volumes highlighted in yellow on Figure 6 represent accumulations that have developed in the bottoms of the depressions after sinkhole development. Since the lakes have no surface water tributaries, these sediment accumulations were derived from slope wash into the lake from the portion of the closed depression that contains the lake and/or slumps from the sides of the depressions.



Figure 5. Map of Big Blue Lake showing SBP profiles. The results of Profiles BB-3 and BB-4 are presented in this manuscript.



Figure 6. SBP Profile BB-3 (Big Blue Lake).

Profile BB-4 – Big Blue Lake

Profile BB-4 (Figure 7) is a much less compressed image that shows not only the structure of the lake bottom bathymetry (as per Figure 6), but it also shows considerable (22 m) penetration into the lake bottom sediments.

Figures 6 and 7 demonstrate that, even though the lake appears to be a single, large sinkhole depression in plan view, it actually consists of a series of overlapped and coalesced individual sinkhole structures. These overlapped sinkhole structures, which are highlighted in yellow in Figure 7, appear distorted because of a complex



Figure 7. SBP Profile BB-4 (Big Blue Lake).

history of multiple subsidence events and development of slump structures.

Figure 7 reveals a smaller (newer?) sinkhole structure forming to the left of the main depression. There are also slump features on the flanks of the main sinkhole depression suggesting that the larger, basinal features and internal sinkholes are continuing to grow.

The maximum observed depth of subbottom penetration is approximately 33 meters. The water surface elevation at the time the SBP profile was acquired was approximately 18 meters MSL. The maximum depth of penetration therefore, would extend down to approximately elevation -15 meters, MSL. Local test borings drilled some 150 meters from the water put the elevation of the top of the FAS at approximately -13 meters, MSL. The disrupted sediment patterns observed on the SBP profile then intersect the FAS, verifying direct connection between the lake and the underlying FAS.

The small, relatively new sinkhole on the left hand side of profile BB-4 is an example of several small, steep sided depressions along the perimeter of the lake. Given that the sinkholes appear to "bottom out" at the top of the limestone of the Floridan aquifer, it appears that there is a limit as to the available sediment to ravel into the Floridan from the center of the lake. Rather, the lake appears to be growing laterally by development of new, lake-margin sinks.

Many of the sandhill lakes in the area show these young, lake-margin sinks in such abundance as to resemble a "string of pearls" (Figure 2).

Conclusions

- SBP is an excellent tool for determination of the origin and geometry of sandhill lakes, which typically have little clay or organic sediment. Penetration is excellent, and sinkhole structures and slump features are readily apparent.
- The sandhill lakes of Washington and Bay counties, Florida, have formed by coalescence of a complex of smaller sinkholes that have a common apparent depth at the approximate top of the underlying limestone of the FAS. The FAS in the area is characterized by many springs and well-developed conduit flow, so the sandhill lakes appear to represent the "headwaters" of the conduit systems.

• The lakes appear to be growing in surface area by development of small, peripheral, lake-margin sinkholes rather than by suffusion or slump of perimeter sand into the existing depression in the lake bottoms.

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IMPROVED IMAGING OF COVERED KARST WITH THE MULTI-ELECTRODE RESISTIVITY IMPLANT TECHNIQUE

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Abstract

Electrical resistivity tomography (ERT, also called ERI) is commonly used to identify geologic features associated with sinkhole formation. In covered karst terrain, however, it can be difficult to resolve the depth to top of limestone with this method. This is due to the fact that the sediments mantling the limestone are often clayrich and highly conductive. The resistivity method has limited sensitivity to resistive zones beneath conductive zones. This sensitivity can be improved significantly with electrodes implanted at depths near the top of limestone, in addition to readings at the surface. Deep electrodes are installed with direct push technology, placing an ERT array in the clay-rich karst cover near the top limestone surface contact. This method, which we are calling Multi-Electrode Resistivity Implant Technique (MERIT), offers the promise of significantly improved resolution of epikarst and cover collapse development zones at the limestone surface sediment interface in heterogeneous karst environments. The technique could also help reduce the effects of cultural features typically encountered by surface electrical resistivity surveys in urban environment.

The results of a case study sinkhole investigation in west-central Florida show the applicability of MERIT. At this site the resistivity array length is restricted to 60 meters. The depth to the top of the limestone lies at ~15 meters. Electrodes were implanted both at the surface and at 10 meters depth every 3.3 meters along a profile 50 meters long. The combination of both surface and deep measurements improves the resolution of the sediment-limestone interface over that from surface measurements alone.

Introduction

Geophysical methods for imaging structures in covered karst often have had limited success because the depth to the sediment -rock interface was greater than the depth of resolution of the survey. This is especially true in urban areas where restrictions in the surface array length limit the depth of penetration. In urban areas cultural features can also have a considerable impact on the geophysical results and complicate interpretation of geophysical results. However the need for full understanding of the sediment/carbonate rock interface in highly heterogeneous karst settings is often a critical problem and geophysical methods remain the most efficient alternative for high resolution imaging between borings.

The resolution depth of electrical resistivity imaging (ERI) surveys is limited by the distance between the furthest electrodes involved in any single reading (e.g. Milsom, 2003). A simple cost effective technique to address this depth restriction is to place electrodes at depth (e.g. Pidlisecky et al., 2006). To fully exploit the available array length, we install electrodes at uniform intervals at depth across the array. With this Multi-Electrode Resistivity Implant Technique (MERIT), deeper features can be imaged. In covered karst, we can then target the sediment /carbonate rock surface interface to image epikarst or possible cover collapse development. By combining measurements with surface and deep electrodes we can also improve imaging of the sediment column above the karst development. In cases where sinkholes are stabilized by grouting, this method could be used to help verify sediment stabilization.

MERIT

With MERIT, the depth of penetration of a resistivity survey can approximately be extended by lowering the electrodes closer to the depth of target horizons (Figure 1). For example, a 33 meter ERI surface array can be expected to resolve features to approximately 7 meters in depth, with greater depths at the center of the array and shallower depths near the ends of the array. If, for example, the bedrock surface is 10 meters below land surface (bls) then the surface geophysical survey will



Figure 1. MERIT method schematic. Electrodes are emplaced at the surface and at depth with direct push technology.

not image the sediment /carbonate rock interface except perhaps at the center of the array. This geophysical survey has missed its target depth by 3 to 7 meters along much of the array. By lowering the ERI array through the unconsolidated sediment, MERIT can get closer to the intended target. Because current can now flow above the electrode array as well as below it, measurements are now responsive to overlying sediments as well as the underlying sediment/carbonate rock contact. To image the underlying contact and voids in the limestone requires that the resistivity of the overlying sediments is simultaneously resolved. This is done by also taking measurements with electrodes implanted at the surface, as in a conventional array.

With the MERIT method, electrodes are installed with direct push technology. Upwards of 150 linear meters of implant installation can be performed in a single day. Referring again to our example for the top of limestone surface at 10 meters bls a 28 electrode implant would require 277 linear meters of direct push drilling at a cost of approximately 1.5 days of direct push installation. The additional cost of installation is offset by the enhanced understanding of specific areas of karst development. In this example, without the implanted electrodes the limestone contact could at best only be identified in the center of the array. Lateral variability and features associated with the development of cover collapse sinkholes could not be imaged.

With time-lapse resistivity profiling (repeated profiles in the same location), the MERIT method could be used for imaging sinkhole development and the effects of ground stabilization efforts. Successive images could be acquired during the sinkhole formation process, and pre and post compaction grouting.

Case Study - Bordeaux Apartments Tampa, Florida

The Bordeaux apartments in Tampa, Florida received national news coverage in July of 2010 after a car in the parking lot was swallowed by a 7 meter diameter cover collapse sinkhole (Figure 2). The sinkhole was adjacent to a 20-unit apartment building and affected part of the structure. Over several weeks the sinkhole continued to enlarge, further threatening the existing structure.

Florida geology and sinkholes

Sinkhole occurrences such as this one are numerous in Florida, and have resulted in substantial number of insurance claims for damages to structures (Schmidt 2005). The development of karst on the Florida carbonate platform has been related to sea level changes of up to 92 to 109 meters below current sea level (Tihansky 1999). These sea level changes have resulted in carbonate rocks being exposed to karst processes (Beck 1986, 1991). In



Car disappears into massive Tampa sinkhole A car swallowed up by a sinkhole near the University of South Florida on Sunday has now Approximate Location of Grouting

Figure 2. Bordeaux Apartments sinkhole, Tampa, FL. Resistivity profile location shown with red line. Boring results are shown in Figure 3. Geophysical surveying was limited to the apartment complex grounds; the spatial constraints on survey dimensions are clear from the photo. North is to the lower right of the photo. The sinkhole was filled with sand at the time of the survey. Hillsborough County, Florida the karst processes have created sinkholes that have affected many structures, irrigation and drinking water wells and farm lands. The cover-collapse sinkhole distribution (FCIT 2008) and development in Hillsborough County is primarily in geologic areas of the county where the cover is 10 to 65 meters thick (Sinclair et al. 1985). The cover is characteristically comprised of undifferentiated Quaternary sediments that overlie Tertiary clay deposits identified as the Undifferentiated Hawthorn Group; these in turn overlie the carbonate limestone of the Tampa Member (Hawthorn Group) that consists predominantly of limestone with subordinate dolostone, sand and clay (Scott et al. 2001). The area of the test case is known locally for a high development of sinkhole occurrences.

Standard Penetration Test borings

Over 23 standard penetration test (SPT) borings were performed on the entire property of the Bordeaux Apartments. Results of borings B1 and B2 near the resistivity line are shown in Figure 3.

In general the site-specific geology was comprised of three basic stratums. From the surface, Stratum 1 consists of 7 meters or less of undifferentiated quaternary sediments of mainly sands. Stratum 2 is comprised of clays and sandy clays of thickness ranging from 6 to 10 meters thick. These sediments vary in clay content and contain limestone fragments near the intersection with the sediment/rock interface. Stratum 3 is comprised of limestone. Depth to limestone in the borings varies from 10 to 19 meters bls. Analysis of the post-remedial underpinning program for 108 underpins indicated the Stratum 3 depths around the perimeter of the structure averaged from 12 to 15 meters bls, however at one location top of limestone bedrock was encountered at 75, meters bls.

Additional analysis came from the grouting program (e.g. Sowers, 1996). A total of 62 compaction grouting points were also installed around the perimeter of the structure and ranged from an average of 12 to 15 meters bls with a single location reaching 44 meters bls. Loss of circulation was recorded at all grout point locations at the point of contact with Stratum 3, except the grout point that extended to 44 meters in which a loss of circulation was recorded starting at 3.3



Figure 3. Borings B2 and B1 (location shown in Figure 1). The uppermost sand constitutes Stratum 1, the intermediate layers constitute Stratum 2, and the underlying limestone constitutes Stratum 3 as discussed in the text.

meters bls and continuing through the entire casing installation. The two deeper locations were located on the east and west sides respectively of the structure affected by the sinkhole activity.

Conceptual Model

The Bordeaux Apartments test site lies in an area identified as having numerous sinkhole incidences. A conceptual model of the sinkhole formation (Beck 1988) was developed prior to the geophysical testing. Two possible cover collapse geometries were considered:

- The sinkhole forms part of a collapse conduit system, which would facilitate flow through the drainage basin to the Hillsborough River to the east of the subject property. The conduit system could possibly extend under the affected building.
- The sinkhole development is isolated to a specific vertical and radial extent.

MERIT Profile

At the time of approval for the use of MERIT, remedial efforts of underpinning and compaction grouting were in progress, and the sinkhole had been filled in with clean sands. It was determined the metal underpinning would have an adverse effect on the MERIT if the profile was positioned too close to the structure. Additional restrictions on profile location included underground power lines and property boundaries. Thus it was determined to place the MERIT profile along the eastern edge of the sinkhole (Figure 2).

The MERIT array was comprised of 18 surface ERI locations and 18 implant locations at 3.3 meters spacing. The MERIT implants were set at 10 meters depth and were in contact with Hawthorn Formation clays and clayey sands of Stratum 2 and within 3.3 meters of the average depth to the top of limestone formation of Stratum3. Two sets of surveys were conducted, one set pre-grouting, and one set post-grouting. In each set of surveys, conventional dipole-dipole and inverse-schlumberger geometries were recorded for both surface and buried arrays, and an additional set of readings were taken in which surface electrodes were used as current dipoles and potential measurements were recorded with buried dipoles.

Data were inverted using Res2Dinvx64 version 4.0 software from Geotomo, Inc. The presence of deep electrodes required the use of the borehole geometry algorithms within the Res2Dinv package (Geotomo, Inc. 2011).

Figure 4 shows the results of the resistivity profile inversion using only the surface electrodes. With surface electrodes, there is no indication of the more resistive limestone below the clays. Figure 5 illustrates the reason for this, namely that the surface survey has very low sensitivity to the 10-13 meter depth of the limestone contact.

Figures 6 and 7 show that when data from the deep electrodes are added, higher resistivities associated with the limestone are imaged (reds and yellows at depth). The sensitivity of the inversion at the 10-13 meter depths of interest is increased dramatically.

Post-grouting surveys looked very similar to pregrouting surveys. The volume of grout used (~30 cubic yards) did not significantly change resistivity images.

Discussion and Conclusions

There are significant misfits between depths of sandto-clay and clay-to-limestone contacts observed in



surface electrodes only

Figure 4. Resistivity profile inversion using data from surface electrodes only. (See Figure 2 for location of profile and borings B1 and B2.) The rms error on this inversion is 11.1%. Only the central 53 meters of the 59 m-long profile are shown. There is no indication of higher resistivities at depth associated with the limestone.



Figure 5. Relative sensitivity of the resistivity survey using data from surface electrodes only. The sensitivity is a measure of how well the resistivity in a given part of the model can be resolved by the data collected. Sensitivity values are normalized by dividing by the mean, and are unitless (Geotomo, Inc. 2011). Resistivities in yellow areas are well-resolved, resistivities in dark red areas are poorly resolved. The surface survey has limited sensitivity below 8 meters depth.



Figure 6. As for Figure 4, but incorporating readings from electrodes at depth. This inversion includes the traditional surface dipole-dipole array, the equivalent dipole-dipole array at 10 meters depth, and readings with current electrodes at surface and potential electrodes at depth. In this inversion, zones of higher resistivity are observed at depths where the limestone was reached in SPT borings.



Figure 7. Relative sensitivity of the resistivity survey data when incorporating readings from electrodes at 10 meters depth. Compare to Figure 5; note the increased sensitivity at depths of 10-13 meters.

the borings (Figure 3) and in transitions in resistivity (Figures 4 and 6). These misfits may be due to significant local 3D heterogeneity that cannot be modeled in the 2D inversion process, or to gradational changes in resistivity across zones of changes in lithology that are more gradual than noted in the boring logs, or to problems in the inversion of relatively noisy data. We note the "cross data", in which current was injected at one level and potential readings were made at another level, were particularly noisy. Optimal acquisition and inversion procedures are a topic of ongoing investigation. With additional case studies and synthetic modeling in progress, we anticipate better understanding of the sources of noise and uncertainty in the resistivity images.

Despite the current limitations, it is clear that at the Bordeaux Apartments the top of the limestone could not be imaged with surface electrodes alone, but could be seen with the addition of the MERIT deep electrodes. The MERIT approach has increased the depth of resolution, and permitted imaging of the target horizon despite the spatial limitation of the site.

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RECONNAISSANCE EVALUATION OF A POTENTIAL FUTURE SINKHOLE USING INTEGRATED SIMPLE SURFACE GEOPHYSICS AND SURFACE MONITORING POINTS

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Abstract

The Arizona Department of Water Resources (ADWR), using satellite-based Interferometric Synthetic Aperture Radar (InSAR) to assess subsidence in parts of Arizona, has identified several subsidence features consistent with potential future sinkholes in an area with several hundred natural evaporite karst depressions or sinkholes. An initial reconnaissance geophysical subsurface evaluation at the most significant of these features was performed in September 2012. Subsurface geo-material strength profiles to depths commonly in excess of 100 meters can be obtained using relatively simple, unobtrusive and inexpensive seismic surface wave (s-wave) geophysical methods such as Refraction Microtremor (ReMi). ReMi can utilize ambient ground vibrations from natural sources or deliberate sources such as vehicle traffic or construction equipment. Shallow ReMi has been applied in conjunction with seismic refraction to characterize shallow subsurface material strength as part of assessing the potential for collapse of an evaporate brine cavern into a large sinkhole in southeast New Mexico, but had not been specifically applied to assessing subsurface conditions in the deeper subsurface above and in the vicinity of a possible impending sinkhole.

Two deep ReMi surface wave soundings and two resistivity soundings using the Wenner array method were performed, one each within and outside of the extent of current subsidence as derived from the InSAR. Surface wave velocity profiles indicated relatively low velocity materials extending to depths of 36 to 50 meters; surface wave velocities within the subsidence zone were lower (weaker material) than surface wave velocities outside the zone. The underlying horizon had high surface wave velocities indicating relatively competent rock. Deep resistivity soundings indicated possible lithologic change at depths of roughly 120 to 150 meters. Results of this work, including interpretations and assessments of knowledge gained, practical additional assessment work that could be performed, and some as yet unanswered questions are presented.

Introduction

A relatively large region of evaporite karst, primarily developed above bedded halites of Permian age, is present south of Holbrook, Arizona (Figure 1). As described by Neal et al. (1998), over 500 karst features such as sinkholes, depressions, fissures and the like are present along and around a roughly 100-km long dissolution front coincident with a structure named the Holbrook Anticline. Recently, the Interferometric Synthetic Aperture Radar (InSAR) group within the



Figure 1. From Conway and Cook (Figure 1, 2013), InSAR study area in relation to the Holbrook salt body, Holbrook anticline and known evaporite karst features.

Arizona Department of Water Resources (ADWR) acquired and processed available satellite-based InSAR data for the region in preparation for monitoring potential future subsidence related to proposed potash mining in the vicinity of Petrified Forest National Park (Conway and Cook, 2013). Several areas of active subsidence were identified in the interpreted InSAR results. The most significant of these features is located primarily in the western portion of Section 3 of Township T16N-R18E. An InSAR interferogram indicating active subsidence at this feature is shown is Figure 2. The sink feature is located in a relatively isolated area, with no known potential geohazard impacts, and thus no pressing public or private safety or economic needs for monitoring or engineering mitigation. The 'Section 3' feature was selected by the Arizona Land Subsidence Interest Group (AzLSG) for further study on a volunteer basis to document observable geologic behaviors or changes that may contribute to knowledge of subsidence and sinkholes.

Part of the study initiated involves measurement of ground displacement. InSAR-derived subsidence information is an interpretation of recent vertical subsidence at the Section 3 feature. ADWR personnel have established Global Positioning Survey (GPS) monuments at the feature and have conducted initial



Figure 2. L-band InSAR interferogram (courtesy B. Conway, ADWR) of Section 3 feature showing extent of local subsidence, RTK survey, subsidence profile A-A' and geophysical sounding locations.

surface elevation profiles to ground-truth future InSAR results. Open ground fissures provide evidence of local horizontal ground displacements at various subsidence feature locations. Several eyebolt monument pairs have been set at open fissures so that future changes in fissure width can be monitored over time.

This paper addresses initial preliminary geophysical characterization of the subsurface at the active Section 3 subsidence feature. Subsurface material parameters that might be characterized include depths or thicknesses of the geologic formations and generalized aspects of geologic material strength. Karst activity can commonly be related to loss of strength in a geo-material mass. Above a carbonate or evaporite dissolution zone, enhanced weathering and fracturing, or even collapse, of the overlying rock mass reduces the overlying rock mass strength. Rock mass strength is related to seismic velocity and can be assessed using seismic methods. In addition to lithologic changes, electrical resistivity may provide information concerning groundwater or changes in rock mass weathering that may be related to karst activity.

Evaporite karst may impact or develop within a subsurface profile that extends to hundreds of meters in depth. Exploratory drilling to such depths can be prohibitively expensive and inefficient in terms of overall site characterization and coverage over a large area. Large-scale geophysical characterization, including 2-D reflection profiling, has been performed recently in the Holbrook basin to support exploration and characterization of minable potash deposits. Although such methods may provide excellent subsurface characterization, the cost for noncritical applications can be prohibitive. Refraction microtremor (ReMi) surface wave seismic and Wenner array resistivity provide means to perform simple, lowcost reconnaissance surface geophysics capable of providing useful subsurface characterization to depths in excess of 100 meters.

Although the Section 3 feature is not associated with a current or pressing hazard, karst-like geohazard behaviors have impacted industrial activity in the region. Neal et al. (1998) summarize historic effluent release events in 1963, 1984 and 1995 into fissures or karst-like features in the Holbrook Anticline area. These events occurred before InSAR remote-sensing technology was available to identify areas of active subsidence. Incorporating

InSAR with other characterization and monitoring procedures may significantly enhance the ability to identify and mitigate some subsidence and sinkhole hazards.

Geologic Setting

Subsidence, sinkhole and karst activity in the area is presumed to be driven over geologic time by dissolution of evaporite deposits within the Holbrook salt body. The Holbrook salt body is located in the southern margin of the Colorado Plateau. As summarized by Neal et al. (1998), rocks of Permian Age, including the Coconino sandstone and salt deposit bearing Corduroy member of the Sedona Group, are relevant in the study area. About 10 km to the west of the Section 3 feature, a group of large sinkholes known as the McCauley Sinks, are overlain by younger Kaibab limestone that serves as a thin near-surface cap at those sinkholes. However, the Kaibab pinches out east of the McCauley Sinks, and Coconino sandstone is left as the upper subsurface member at the Section 3 feature. Johnson (1962) describes the Coconino in the nearby Snowflake-Hay Hollow area as "In places the sandstone is tightly cemented with silica, but the degree of cementation varies considerably from place to place as well as vertically in any given section." Without well log control in the vicinity, the local thickness of the Coconino is unknown. Based on limited historic geophysical log data in the region (Figure 4 in Neal et al. 1998), it may be about 200 meters or less in thickness at Section 3.

Underlying the Coconino sandstone is the Corduroy Member of the Sedona Group. Included in the Cordurov Group are shales, anhydrites, halite (salt), and salt and shale. Dissolution of salt in the Corduroy Member is considered to be the primary subsidence mechanism for generating karst. Neal et al. (1998) indicate that dissolution has likely been continuing since the Pliocene. The Holbrook anticline, which involves at least the rock profile above the Corduroy Member salt, is more than 10 km to the southwest from the Section 3 feature. Significant bedrock fracturing activity, providing concentrated pathways for groundwater to access soluble formations, tends to be concentrated closer to the anticline. It is also anticipated that bedrock overlying zones of large-scale dissolution would tend to be fractured or perhaps even brecciated as the rock column subsides downward while dissolution progresses.

Historic and recent depths to groundwater in stock wells located about 2 km east of the Section 3 feature, are

recorded in ADWR databases (ADWR, 2012). A depth to groundwater of 91 meters is recorded for Well A(16-18)02ACB in 1946. Depths to groundwater at Well A(16-18)02BAD at elevation 1,664 meters above mean sea level (amsl) are reported to be about 112, 120 and 121 meters in 1968, 1975 and 2009, respectively.

Surface Elevation and Subsidence

The regional ground surface trend in this portion of the Holbrook Basin is a gradual slope towards the Little Colorado River to the north-northeast. That regional trend is apparent in the south to north RTK survey profile performed by ADWR (Figures 2 and 3).

A local ground surface elevation trend is included in Figure 3. This trend assumes that the RTK survey southern and northern ends are consistent with a ground surface trend in the absence of local subsidence. The RTK surface elevation survey indicates that subsidence has occurred in the southern portion of the Section 3 feature. Assuming a uniform grade prior to local subsidence activity, possible subsidence could have been as great as 12 meters or more over a profile distance of about 200 meters. Possible subsidence is reduced towards the north, and is typically 2 meters or less compared to the no local subsidence trend.

The InSAR current subsidence pattern covering December 2006 to February 2011 presented at profile A-A' is closely related to, but significantly different from the apparent pattern of historic subsidence derived from the RTK survey. The southern end of the RTK profile indicates a steep increase in apparent subsidence over



Figure 3. Comparison of RTK surface elevation survey with L-band InSAR-derived subsidence on a south to north profile through Section 3 feature (Figure 2).



Figure 4. Resistivity equipment including meter (yellow box), electrode cable spools and water jugs; water is added at electrodes to improve contact with ground.

a distance of about 100 meters. InSAR-derived current subsidence in that area is negligible. The area of greatest apparent subsidence, typically about 12 meters, along the next 200 meters of RTK survey profile, has only minor InSAR derived subsidence up to about 0.05 meters in four years. However, the apparent subsidence rapidly decreases at the northern edge of this deep local area. Where the measured apparent intra-basin subsidence is nearing its minimum, the current active subsidence is near its maximum. The point of highest InSAR-derived subsidence is at the northern lip of the local apparent subsidence area. A benchmark was established in this area for future GPS elevation measurements and to serve as an RTK survey base. Active subsidence then gradually tapers off to the north. If the current rate of subsidence is projected 100 years into the future, the local deep subsidence area would increase in size to the north, but the maximum subsidence depth would not significantly increase.

Anticipated Geophysical 'Targets'

Anticipated geophysical measurement results or targets can be developed based on the geologic setting, apparent local subsidence pattern and magnitude, and current subsidence trend. Confirmation or refutation of anticipated geophysical results would assist the process of understanding and characterizing details of conditions and mechanisms driving continued development of karst in this area. Deep sounding electrical resistivity results are anticipated to be influenced by groundwater conditions and geologic material lithologies; both impact development of karst. Seismic velocity profile results are anticipated to be influenced by geologic material strength; material strength can be significantly degraded by karst activity.

The Coconino sandstone is primarily of Aeolian origin. Given both a deep groundwater table and a rock fabric largely lacking in conductive clay particles, high resistivities can be anticipated in the upper subsurface consisting of the Coconino. Lower resistivities can be anticipated in underlying shales at the top of the underlying Corduroy Member. Thus, deep Wenner array resistivity soundings can be anticipated to encounter a significant, deep high resistivity horizon underlain by a low resistivity horizon. An estimate of thickness of the overlying Coconino might be interpreted from resistivity sounding results.

Seismic velocity relates quantitatively to material modulus, and thus is strongly related to geologic material strength. Since shear wave (s-wave) velocity is minimally influenced by saturation, s-wave velocity is an indicator of material strength below the groundwater table. An s-wave velocity profile may be estimated using surface wave methods such as ReMi. As a well-known canyon cliff-forming formation on the Colorado Plateau, the Coconino sandstone can be anticipated to have high seismic velocity when relatively competent. However, if significant dissolution in underlying salt beds result in a loss of support under the Coconino, distortion, fracturing and perhaps even brecciation and collapse of the otherwise intact formation into the underlying void space forming sinkholes, is anticipated. High measured s-wave velocities are anticipated in the Coconino where underlying dissolution collapse has not occurred and the formation is relatively competent. Low measured s-wave velocities are anticipated in the Coconino where underlying dissolution has occurred and the overlying formation has been fractured, distorted or brecciated.

Initial Geophysical Reconnaissance

Initial geophysical reconnaissance at the Section 3 feature was performed by a small group of volunteers on 15 September 2012. Two each deep Wenner array resistivity and ReMi surface wave soundings were completed at locations shown in Figure 2. Based on existing data interpretation, Soundings Location 1 was generally assumed to be outside the area of active subsidence to attempt to provide a baseline for the subsurface geologic profile without influence of local subsidence. Soundings Location 2 was centered near the RTK base in the area of greatest current subsidence magnitude to attempt to provide some initial characterization of geomaterial properties in the area of active subsidence.

Resistivity Measurements

Resistivity measurements were made using the Wenner method. Four electrodes are set into the ground, making electrical contact with the earth, along a line at equal spacing. An electrical current is applied to the two outer electrodes, and the voltage difference in the resulting electric field is measured at the two inner electrodes. An apparent resistivity, a function of voltage, current and geometry, is determined for that electric field. The electric field forms within a roughly hemispherical volume of earth with radius of the electrode spacing. A sounding consists of a series of progressively larger electrode spacing measurements that sample progressively deeper volumes of earth. The depth of investigation is difficult to assess, but is less than the largest electrode spacing. Interpretation consists of developing mathematical models of layer thicknesses and resistivities that is matched to the measured resistivities.

An L-and-R Ultra-Minires resistivity meter was used with resistivity electrode spacings of 1.5, 3, 6, 15, 30, 60, 101, 152, 229 and 305 meters to complete the resistivity soundings. Electrical contact between the stainless steel electrodes and earth was established by driving the electrode into the dry to very slightly moist ground, removing it, filling the hole with water, and then re-driving the electrode into the hole. Markings on cables and reels were used to set electrode positions at the longer electrode spacings.

Resistivity Interpretation Results

Interpretations of the two resistivity soundings were consistent with high resistivity unsaturated rock lacking significant fines within the rock fabric to depths of about 100 to 130 meters. Below a thin surficial horizon, interpreted resistivity at Sounding R-1, located outside the active subsidence area, ranged from about 4,400 to 8,100 ohm-meters in assumed Coconino sandstone above the groundwater table. Below a depth of about 128 meters, the interpreted resistivity dropped to about 47 ohm-m. This significant resistivity drop may reflect saturation in the Coconino below the water table. Alternatively, it may indicate the top of the underlying Corduroy Member, although a resistivity of 47 ohm-m is typically high for a shale below the water table. It may also indicate a combination of a relatively thin section of saturated Coconino and somewhat deeper underlying low resistivity shale. At a minimum, the top of the Corduroy Member can be interpreted to lie at a depth greater than about 128 meters at Sounding 1. It must be understood that the resistivity interpretations result in non-unique solutions and assume ideal geometric models such as horizontally uniform layers or horizons.

Resistivity Sounding 2, located in the active subsidence area, had similar interpreted results (Figure 5) as Sounding 1. The interpreted top of the lower resistivity horizon, at a depth of about 111 meters, was shallower at Sounding 2 than the 128 meter depth at Sounding 1. Subsidence along the Sounding 2 profile might be a possible contributor to explain a shallower depth to lower resistivity. Discarding the measurement at 15 meter electrode spacing, the interpretation curve fit to the field data was excellent, as shown in Figure 5. An anomalous reading at the 15 meter electrode spacing could be explained by an observed open fissure exposing shallow bedrock near the northern outer current electrode. Such a feature extending into the subsurface could influence (partially blocking) the current path near that electrode.

ReMi Seismic Measurements

Refraction Microtremor (ReMi) is a seismic surface (Rayleigh) wave method (Louie, 2001; Optim, 2004) that utilizes surface wave dispersion physics to characterize the subsurface as a vertical 1-dimensional s-wave profile. Like vertical sounding using resistivity,



Figure 5. Interpretation of resistivity Sounding 2 showing apparent resistivity measurements, curve fitting and resulting interpretation.

the interpretation process leads to non-unique solutions. If available, other subsurface information can help to constrain the non-unique solutions. Surface wave methods can characterize the subsurface profile below velocity reversals and below the water table where compression wave methods (such as standard seismic refraction) can be severely limited.

ReMi can also be used in naturally and culturally noisy environments and can use ambient ground vibration as a passive surface wave energy source. Depth of investigation is constrained by the wavelength penetration of the surface waves into the earth; depths of investigation greater than 100 meters are often attainable if sufficiently low frequency surface wave energy is available. Transcontinental railroad traffic passing through the Holbrook basin several kilometers to the north of the study site provided a ready source of ambient low frequency surface wave energy.

The field procedure included laying out cabling for a 24-geophone array at 7.6 meter geophone spacing, and setting and leveling the 24 low frequency (4.5 Hz) geophones. Overall array length was 175 meters. Arrays were oriented roughly northnortheast to point towards the general direction of the distant railroad energy source. A 24-channel seismograph was used to collect 12 or 24 second ambient surface wave datasets at sampling intervals of 1 or 2 milliseconds. Since railroad traffic was many kilometers away, geophone channel gains were set to high amplification; no filtering was applied during data collection.

The interpretation at ReMi Sounding 1 outside the area of active subsidence is presented in Figure 6. An immediate difference of the ReMi interpretation and general concept of the geologic profile is a relatively low surface wave velocity in the upper 50 meters of the subsurface. At a velocity less than 700 meters per second (m/s), the upper 50 meters of the Coconino sandstone is not a relatively competent, high strength rock material. At best, it might be considered equivalent to a very soft rock, but may exhibit soil-like characteristics (from an engineering perspective). Below about 50 meters, the greater than 2,000 m/s surface wave velocity is indicative of competent rock.



Figure 6. Interpretation of ReMi Sounding 1 showing spectral amplitude as a function of surface wave velocity and frequency, dispersion curve fitting and resulting interpretation.



Figure 7. Interpretation of ReMi Sounding 2 showing spectral amplitude as a function of surface wave velocity and frequency, dispersion curve fitting and resulting interpretation.

The interpretation at ReMi Sounding 2 within the area of active subsidence is presented in Figure 7. The relatively low surface wave velocity is in the upper 36 meters of the subsurface, but has an even lower velocity of about 520 m/s. From an engineering perspective, it might be considered equivalent to a very dense or cemented soil. Below about 36 meters, the greater than 2,000 m/s surface wave velocity is indicative of competent rock. Thus, a relatively competent rock portion of the Coconino sandstone is interpreted to be present at the Sounding 2 location in the area of most active subsidence.

Geophysical Anomalies

Even though quantitative analysis may require ignoring or discarding some anomalous data, anomalies in geophysical data can provide critical information to assist in understanding subsurface conditions. As was previously noted, a resistivity reading at Sounding 2 was discarded for interpretation due to the presence of an open fissure (Figure 8) near an outer electrode. The Sounding 2 ReMi seismic array was deployed in this same area. Anomalous signal loss in ReMi data from this location is shown in Figure 9. A coherent surface wave signal with a frequency of about 4.4 Hz appeared to be blocked between traces 9 and 10 from the right in Figure 9 on the trace printout. That type of attenuation anomaly is consistent with an open fissure in the subsurface with sufficient continuity and depth to block the signal propagation. From the interpretation shown in Figure 7, surface wave velocity at 4.4 Hz is about 1,000 m/s, resulting in a wavelength of about 227 meters. Since most of the surface wave energy propagates within the upper quarter to half wavelength of the surface, such attenuation could indicate an open fissure that may extend well into the subsurface.



Figure 8. Open fissure along surface geophysical arrays alignment. Note near-surface bedrock and relatively uneroded adjacent soil surface that indicates recent fissure development.



Figure 9. Anomalous surface wave signal loss in ReMi Sounding 2 field data at open fissure. All geophones are set at equal gains (84 db). Note loss of coherent signal from right to left between the 9th and 10th traces.

Discussion

Initial geophysical reconnaissance has begun to illuminate subsurface conditions at the Section 3 feature to understand the active subsidence documented by InSAR and possible previous subsidence indicated by the RTK elevation profile survey. However, initial results have also raised questions about assumptions of subsidence mechanisms. The interpretation of a high velocity horizon at Sounding 2, consistent with relatively competent Coconino sandstone in the area of highest current subsidence and the edge of greatest apparent subsidence, does not indicate significant local disruption of the geologic profile from dissolution in the underlying salt.

Is there an alternative explanation for the apparent 12 meters of subsidence that may have occurred just to the south of the highest current subsidence? The shallower low velocity upper Coconino horizon might provide an explanation. If differences in seismic velocity in the upper 36 to 50 meters inside (lower velocity) and outside (higher velocity) the active subsidence are correct, changes in the weak rock fabric similar to collapsible soils might explain some of the apparent subsidence. As described previously (Johnson, 1962), the Coconino sandstone has a cemented structure. If that cemented structure is disrupted, the particles could collapse into a more dense structure, resulting in surface subsidence.

Seismic velocity can be related to geo-material porosity and modulus based on concepts of Percolation Theory as described by Sahimi (1994). Rucker (1998, 2000, 2008), has developed these relationships for cohesionless granular, fractured or jointed geo-materials that behave as 'physical gels', where material mass particle contact points freely move (roll) relative to each other. When adjacent particles are cemented, bonded or welded in 'chemical gels' such as welded tuff or unfractured limestone, they are not free to move (roll) relative to each other. Relationships of surface wave velocity to a geo-material mass density are presented in Figure 10; data points are discussed in Rucker (2008).

The ReMi Sounding 1 horizon with surface wave velocity of 700 m/s at depths of 14 to 50 meters, may behave as a chemical gel material that, although relatively low density, has an intact cemented rock fabric relatively unaffected by subsidence or karst activity. It might have a mass density (Figure 10) as low as perhaps about 1,400 kg/m³. The same horizon within the subsidence area may have suffered disruption of the rock fabric as the rock mass has been stressed and degraded, perhaps through mass movement and or weathering induced through fissures. With loss of cementation or bonding, the rock material structure might behave as a physical gel material that has consolidated or collapsed into a more dense structure. As a physical gel material, the analogous ReMi Sounding 2 horizon, with surface wave velocity of 520 m/s at depths of 14 to 36 meters, might have a mass density (Figure 10) of about 1,950 kg/m³. The change from chemical to physical gel behavior could cause the horizon volume to decrease to roughly (1,400 / 1,950 =) 71 percent of its original volume. Since 71 percent of 50 meters is about 36 meters, a change in the rock material from a chemical to a physical gel behavior is consistent with the difference in the interpreted horizon thickness. Also, the difference of 50 meters and 36 meters is 14 meters, which is close to the roughly 12 meters of apparent subsidence measured by the RTK elevation survey.

Limitations of 1-Dimensional Methods

Charaterization of karst can be a highly complex and variable 3-dimensional process. The applicability of relatively simple 1-dimensional 'sounding' methods may be, in part, a function of other available information about a karst site and the scale of measurements being made compared to the scale of the phenomena being evaluated. Scale is a primary variable. When a target



Figure 10. Percolation Theory-based relationships between seismic velocity and mass density for physical gel and chemical gel geo-materials. When bonds in a chemical gel material are disrupted, that material can revert to a physical gel as shown.

is small relative to the capability of the geophysical measurement, potentially critical variations within the target cannot be assessed. However, for a target area that is large relative to the capability of the geophysical measurement, a series of 1-dimensional measurements can be performed to develop some understanding of the target in 2- or 3 dimensions.

If nearby borehole or well logs, or other detailed data, are available at a site, then surface geophysical soundings may be of limited value, or may have value in verifying whether conditions are similar to or change from nearby known conditions. When no other local subsurface geologic information is available, reconnaissancelevel geophysical soundings may be a primary feasible economic means to obtain preliminary subsurface information to begin a site investigation.

Conclusions and Recommendations

InSAR has allowed the identification of in-progress subsidence in a geologic setting of probable dissolution-induced subsidence and karst development. Straightforward surficial survey and simple surface geophysical measurements have been applied to initiate a baseline of data to improve understanding of possible subsidence and karst mechanisms. Initial results from these measurements indicate the likelihood of complex, multiple and subtle processes at work at the Section 3 feature, and by inference, other karst areas within the Holbrook Basin.

The authors recommend that a continuing, possibly informal program of mapping, monitoring and measurements proceed at this feature. Detailed mapping of surficial fissures, pressure ridges and dip and strike trends of exposed bedrock should be performed and analyzed in a context of local topography and InSAR-derived patterns of current active subsidence. Such tasks could be incorporated into university-level geology class or club activities and other knowledgeable, technically capable volunteer groups. Further simple surface geophysics might then continue to be strategically deployed based on improved knowledge of subsidence and karst-related features and continuing InSAR monitoring. Due to cost, land ownership constraints and the absence of an urgent geohazard condition, future exploratory drilling is not foreseen at the Section 3 feature.

Results presented here are an initial reconnaissance effort to begin to understand the Section 3 feature. As information concerning this feature increases through further investigation and monitoring, knowledge and understanding of the feature and the mechanisms acting on it will improve. Hypotheses of subsidence behavior can be developed, tested and refined. Knowledge and experience gained by such a program, even if informal, will further demonstrate the value of incorporating multiple tools and approaches, including integrated simple surface geophysics, for characterization and monitoring of subsidence and karst.

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GROUND-PENETRATING RADAR, RESISTIVITY AND SPONTANEOUS POTENTIAL INVESTIGATIONS OF A CONTAMINATED AQUIFER NEAR CANCÚN, MEXICO

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Abstract

Geophysical surveys were made over portions of the Cancún municipal well field in the Yucatán Peninsula of Mexico, approximately 20 km southwest of the city of Cancún, in order to identify karst conduits that channel contaminated surface waters into the main aquifer. Specifically, ground-penetrating radar (GPR), vertical electrical soundings (VES) and spontaneous potential (SP) surveys were employed to identify these conduits and detect water movement through them.

Cancún s municipal water supply has frequently been affected by fecal coliform bacteria and other contaminants. Water supplies are largely derived from highly permeable fractured karst limestone aquifers characterized by rapid transport of microbial and chemical contaminants from the surface to subsurface unconfined and confined aquifers. Quaternary and Tertiary limestone bedrock outcrops across this entire area, which exhibits less than 3 m of local relief.

Schlumberger array VES were made at two locations.. One sounding revealed a 3-layered structure consisting of a 177 ohm-m layer 2.1 m thick, (probably weathered limestone), overlying a high resistivity layer 8.2 m thick (massive limestone with some small caves), overlying saturated limestone (45 ohm-m). The other sounding could not be successfully inverted due to lateral resistivity variations. Twenty-one GPR profiles were also made with 50- and 100-MHz antennas along roads passing through the well field. In the upper 5 m these profiles reveal cut-and-fill structures and a myriad of diffractions that may represent collapsed and filled sinkholes or solution-enlarged fractures. A major interface delineated by GPR at about 6-8 m depth probably represents the water table. An unusual transparent zone (absence of GPR reflections) was also visible in one GPR profile

made near a surface conduit. This transparent zone was at least 1.5 m wide and extended over several meters depth. SP measurements near this conduit during a rainstorm revealed a peak-to-peak variation of 16 mV, suggesting SP may also be a viable method for mapping subsurface water movement in this well field. The overall implication of this work is that geophysical methods are valuable in delineating recharge points and shallow contaminant pathways, and should be used more extensively in this part of the Yucatán Peninsula to support groundwater investigations.

Introduction

The municipal water supply for Cancún, in the northeastern Yucatán Peninsula of Mexico, has been degraded often by fecal coliform bacteria and other contaminants. Water supplies for the Yucatán are largely derived from highly permeable fractured karstic limestone characterized by rapid transport of unfiltered microbial and chemical contaminants from the surface to subsurface unconfined and confined aquifers. The objective of this study is to identify geophysical techniques that could be of use in identifying these infiltration conduits.

In early January 2012, a team from Northern Illinois University (NIU) traveled to Cancún, Quintana Roo, Mexico to join scientists from the Centro de Investigación Cientifica de Yucatán (CICY) to perform exploratory geophysical work to identify infiltration conduits. Geophysical techniques were chosen based on instrumentation traveling economically to the study site. The GPR and SP efforts were directed toward identifying specific karst conduits that provide rapid recharge and contaminant pathways that lead from the land surface to the aquifer. VES were used to examine the overall vertical electrical structure of the well field aquifer, and assess lateral heterogeneity that might necessitate 2D resistivity surveys in the future.

Geological Setting

The study site is located within a municipal well field near the Cancún International Airport, approximately 20 km southwest of the city of Cancún. This area lies within the Yucatan northeastern coastal plain (Isphording, 1975) on a low upland between the eastern coastal ridge and swale complex and the Holbox fracture system to the west. Pliocene – Upper Miocene limestone of the Carillo Puerto formation outcrops, or is covered by only a few cm of soil, beneath thick jungle cover (Smart et al., 2006). The Carillo Puerto formation is over 300 m thick, overlying largely carbonate ejecta from the Chicxulub impact structure 200 km to the west. This ejecta, in turn, overlies carbonate Cretaceous and Jurassic units containing evaporites (Perry, 2002).

Hydrogeology, Contaminants and Karst Features

Groundwater is the only available fresh water source in the northeast Yucatan peninsula. Groundwater resources, however, are under considerable strain from extensive pumping and development along the Caribbean coast, as well as smaller-scale developments directly over and adjacent to the well field. The average recharge rate in the area ranges from 200-500 mm/year, and regional groundwater flow is presumed to be easterly beneath the study area, discharging at the coast, about 25 km away (Bauer-Gottwein et al., 2011).

The survey area is regarded as a contaminated part of the Cancún municipal well system, which consists of several well fields. Obvious contaminant pathways are open fractures and conduits in the limestone that are directly connected to the shallow drinking water aquifer. There isn't significant soil on the surface to allow for filtration of contaminants. The most common contamination is related to feces – pathogens, nutrients, etc. This area is not industrial – contaminants are derived from small-scale agriculture, tourism, or residential activities. Refuse is also (unofficially) disposed of in some of these solution openings.

Numerous publications discuss the cave systems of northeast Yucatan, including Thomas (1999), Beddows (2002a, 2002b, 2003) and Smart et al. (2006). The Riviera Maya cave systems, consisting of several long caves 10s of km long and 10s of meters wide are the most extensively studied and mapped. Navigable caves have not been identified within the study area, however, despite the common occurrence of small-scale conduits and collapse features (generally less than 1 m across). visible at the surface. Thus no cave maps exist in the study area.

Methodology

Three areas were investigated in detail over the southwest Cancún well field, sometimes referred to as the aeropuerto well field (outlined with squares in Figure 1). These sites were near Well (Pozo) 49A (Area 1) and at the intersection of two of the roads used to service the well field (Area 2), and near Well 40 (Area 3). The three areas we investigated geophysically were essentially targets of opportunity: Well 49A was open and being serviced (Area 1), (2) a visible conduit, partially filled with trash and accepting rainwater (Area 3) near the intersection of the well field service road, Well 40 and the Ruta de los Cenotes, and a service road intersection with nearby apparent depressions in the ground surface that may have been filled sinkholes (Area 2). In general geophysical surveys were made along roads. Road "pavement" consists of the limestone bedrock.

Most of surveys involved GPR since this highresolution technique has the potential to identify conduits transmitting contaminants from the surface into the aquifer. Reviews of GPR for karst settings may be found in Al-fares et al. (2002) and Anchuela et al.



Figure 1. Map of study areas showing roads and cenotes. Inset shows location of study area within the NE Yucatán (inset after Beddows, 2003).

(2009). The GPR unit used was a Sensors and Software pulseEKKO IV, with 50, 100 and 200 MHz antennas. A total of 21 GPR surveys were made, including three common-midpoint (CMP) surveys to determine GPR wave velocity and 18 profiles of various lengths. All surveys were along straight lines, although some lines were run parallel to each other to examine the areal extent of certain features. Profile lengths ranged from 4 to 40 m. Antenna separation depended on antenna frequency and antennas were manually moved along profiles in 10 cm increments. In the GPR sections depth is computed from average GPR wave velocity (between 0.09- 0.12 m/ns) determined from the CMP surveys. Shape- matching of diffraction hyperbolas was also used to establish velocity. GPR processing consisted of dewowing (Davis and Annan, 1989), low-pass filtering to reduce high-frequency noise, aligning the air-wave arrival and shifting traces, if necessary, to account for time-zero errors or instrumental drift. Both variablearea and color displays were employed, generally using automatic gain control with a maximum gain of 200. Depths were determined using the average GPR wave velocity measured in the CMP surveys or through diffraction fitting.

The SP and VES surveys were both run from the same system, an ABEM SAS 300B Terrameter (for more information about SP and VES surveys in karst areas see Ford and Williams [2007]). The VES utilized four stainless steel electrodes pounded into the thin topsoil overlying the bedrock in a Schlumberger configuration. SP surveys were made over several intersecting lines near the pumping wells, as well as over apparent karstic conduits (holes visible at the surface) during rainfall. The target was small voltages induced by moving water (streaming potentials) (Reynolds, 2011). Two porous pot electrodes filled with copper sulfate solution were utilized to collect the data. One was fixed as a reference electrode while the other acted as a roving electrode and the unit recorded the difference in potential (in mV) between these electrodes. The fixed electrode was at least 10 m from the roving electrode.

Ground truth calibration

Very little ground-truth data is available for the study area. The municipal wells for this area were not logged, and any records made during drilling (during the 1970s and 80s) were not immediately available from the Cancún Municipal Water Department. During the geophysical surveys one wellhead had been removed for maintenance (Pozo 49A); the water level in this well was measured at 6.2 m beneath the surface. It is not known if this water level represents a confined aquifer or not. Most likely it represents the water table, since no apparent confining layers are present. During the 4-day period of the geophysical surveys no maintenance personnel showed up, and the well was left open.

The nearest vertical outcrop is at the Calica quarry, near Playa del Carmen, approximately 30 km directly south of the study area (Figure 2). The flat lying strata within this area of the Yucatán make this a plausible comparison to the study area.

A heavily weathered zone, approximately 3 m thick, overlies a massive zone 8-10 m thick, containing caves. The floor of the quarry was wet with some standing water and small ponds, suggesting the water table is at the base of this massive unit, placing the water table approximately 11-13 m beneath the surface. Other wells at Calica penetrate the freshwater /saltwater interface at about 30 m depth.

Results

GPR GPR appea

GPR appears to have successfully identified the water table and other layers in the upper 13 m in Area 1, as shown by Figure 3 (50 MHz antennas). In Area 2 (Figure 4) GPR imaged what appears to be a disrupted zone between depths of 4 and 12 m containing perhaps the remnants of collapsed caverns and/or sinkholes that have been filled. These appear bowl-shaped or gently



Figure 2. Cross-section of limestone at the Calica quarry, near Playa del Carmen, scale bar is in upper left.

undulating. Other GPR sections showed steep hyperbolic diffractions, possibly generated by conduits, small caves, or other sharp heterogeneities. Figures 5 and 6, from Area 3, depict a reflection-free "transparent zone" directly below a surface conduit (a hole at the surface that rainwater was flowing into). This transparent zone may be a largely air-filled conduit producing unusual refraction of GPR waves.

VES

Schlumberger resistivity arrays were used for VES in Areas 1 and 2 (Figure 7). Electrodes were inserted into the thin soil (zero to 5 cm thick) covering bedrock. No electrode conditioning was employed.

The VES in Area 1 was interpreted as a 3-layered resistivity model consisting of a 2.1 m upper layer of resistivity 177 ohm-m, overlying an 8.2 m thick 465 ohm-m layer, overlying a 45 ohm-m half-space layer, which probably represents saturated limestone. This structure is consistent with what was observed at Calica (Figure 2), although thicknesses are different. The lower resistivity upper layer is probably highly fractured and weathered limestone, the high-resistivity middle layer may be a compact relatively unweathered limestone and may contain air-filled cavities and voids in its upper portion, as shown in Figure 2, resulting in its elevated resistivity. The lowermost layer probably represents





Figure 4. GPR section across part of Area 2, showing disrupted reflections and possible collapse features. Antenna frequency was 100 MHz, separation 1 m and the step size between traces 0.1 m.



Figure 5. GPR section across part of Area 3. Antenna frequency was 100 MHz, separation 1 m and the step size between traces 0.1 m.

Figure 6. Same GPR section as in Figure 5, but plotted with variable density and in color, to denote areas of signal loss.

saturated limestone and/or the saline water zone. The VES in Area 2 was severely affected by lateral resistivity variations and could not be interpreted as a layered model with high confidence. This suggests 2D resistivity should be employed in future surveys in Area 2.

SP

SP data was also collected both in Areas 1 and 3. Several profiles were collected along cross shaped, intersecting lines near the pumping wells. While the lines were not very long, the wells were pumping at a rate of about 1500 liters/min and very little change in the potential was noted. This could be due to the conduit flow nature of the aquifer, i.e. the SP lines might not have passed near the hydraulically active fractures those wells were drawing from (streaming potentials that generate SP are discussed in Reynolds [2011] as well as other geophysical texts). The SP surveys, however, recorded significant changes in potential (about 16 mV) over a conduit where rainwater was infiltrating, as shown in Figure 8. This fracture was also imaged using GPR in Figures 5 and 6.


Figure 7. Resistivity sounding made with a Schlumberger array in Area 1, along with the layered model inverted from the sounding curve.



Figure 8. SP profile across a flowing conduit in Area 3.

Conclusions and Future Work

This study evaluates the feasibility of using geophysical techniques to locate hydraulically conductive infiltration conduits in a karstic aquifer utilized as a water source by the City of Cancún. Three techniques were evaluated: GPR, VES and SP. The water table, at approximately 6-7 m depth, was visible with GPR. VES provided a 3-layer model with a moderate resistivity upper weathered layer overlying a high resistivity layer perhaps representing compact limestone with air-filled voids in its upper part. The lowermost layer was much lower resistivity, suggesting it is below the water table or even in the saline zone. Some GPR profiles also showed apparent (filled) collapse features, as well as transparent zones devoid of reflections. SP surveys worked best across a flowing conduit observed at the surface, where an anomaly of about 16 mV was recorded, presumably due to streaming potentials.

Future work should concentrate surveys over known voids or high permeability zones, so that geophysical

models may be verified by ground-truth. Different methods should also be employed that would allow for more expansive and contiguous data sets such as electromagnetic (EM) profiling, conducting GPR using towed antennas, employing very low frequency (VLF) and other systems. This would allow the extent of the conduits to be better characterized and help to understand the complex flow network underground, along with possible contaminant routes.

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TYPICAL METHODS FOR FORECASTING KARST COLLAPSE IN CHINA

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Abstract

The aim of this paper is to describe improvements in the accuracy of forecasting karst collapse by summarizing the methods and analyzing their advantages and disadvantages. The forecasting methods were classified as geophysical surveys, monitoring of triggering factors, and strain measurements using optical fibers. Geophysical surveys can directly identify soil cavities, but the precision and depth of exploration are limited by equipment parameters and geological conditions. For example, ground penetrating radar can discover a soil cavity when the overburden layer is less than 15 m thick, and frequent scanning can determine changes in the soil cavity and predict sinkhole collapse when combined with a balance arch model. Monitoring of triggering factors is widely used to forecast karst collapse when the opening is caused by pumping, as the dynamic groundwater conditions can be acquired in real-time. However, the prediction criteria can be very difficult to obtain. In this paper we recommend a method based on the relationship between the times when anomalous monitoring data appear and the time a sinkhole opens. Using optical fibers to forecast karst collapse is the most advanced technology currently available in China. The location and time of sinkhole opening can be forecast by this method in theory, but some key issues have yet to be resolved. These issues include the strain correlation between the optical fiber and the soil, the effect of temperature on the optical fiber strain and the method of laying optical fibers in the soil. Finally, some proposals are suggested in the hope that they will generate public discussion, reducing the damage caused by karst collapse.

Introduction

In most studies of sinkholes, forecasting has been mainly based on geophysical surveys, monitoring of triggering factors, and strain measurements of the soil using optical fibers. Geophysical survey methods have been widely applied since the 1960s to solve karst geology questions including karst collapse. Direct current (DC) resistivity techniques have been used in cave detection because of its low costs, simple field procedures and the rapid interpretation of data (Vincenz, 1968; Smith, 1986; Panno et al, 1994; Batayneh and Al-Zoubi, 2000). In recent years, ground penetrating radar (GPR) techniques have become the most popular geophysical tool for identifying and locating subsurface karst features, such as cavities, conduits and fractures (Ulriksen, 1982; Garsmueck, 1996; Martin-Crespo and Gomez-Ortiz, 2007). Other methods, such as microgravity (Arzi, 1975; Blizkovsky, 1979; Butler, 1984) and the electric-magnetic method (Kaspar and Pecen, 1975) have been used only infrequently. Geophysical prospecting methods are effective for forecasting karst collapse, but the precision, continuity and depth of the exploration are limited by equipment signal-to-noise and geological complexities.

Monitoring for trigger factors based on the groundwater pressure has become more common and can be an effective method for forecasting karst collapse (Lei et al, 2002; Li et al, 2005; Meng et al, 2006). The greatest benefit from this method is the real-time acquisition of hydrodynamic groundwater information. However, laboratory studies of the seepage deformation test have indicated that errors often appear due to discrepancies in the structures and physical-mechanical properties of the soil, even within a single layer. Thus, the smallest experimental marginal hydraulic gradient usually is adopted as a threshold for engineering safety, but this leads to a very low forecasting accuracy.

Soil strain measurement using optical fibers is the latest method for predict karst collapse. Model tests show that there is a very good relationship between the strain in the optical fiber and the soil deflection when a sinkhole opens (Jiang et al, 2006). However, some key techniques need to be implemented to understand the

strain relationship between the optical fiber and the soil (Meng and Guan, 2011).

In the paper, the principles underlying each method are introduced first, followed by some examples of the forecasting results. Finally, the merits and disadvantages of each method are analyzed and some suggestions are provided for improving the forecasting precision and reducing the harm from karst collapse.

Ground Penetrating Radar (GPR) Surveys

The simplest and most popular method for forecasting karst collapse is ground penetrating radar (GPR) in geophysical surveys. This technique can directly identify soil cavities (Figure 1). Frequent scanning using the GPR is very important to predict sinkhole openings at the ground surface. If changes in the soil cavity arch from the GPR map fit the prediction model, a sinkhole will open.

The GPR modeling for predicting the sinkhole is based on an idealized balance arch as shown in Figure 1, where: σv is the natural vertical stress; τ is the natural horizontal stress; h is the height of the arch; b is the half span; and f is the Protodyakonov coefficient (f = $\sigma v/10$) (Protodyakonov, 1962). The coordinates x and y describe the location of A on the arch LOM in the Figure 2. The equilibrium equation of the arch is $y = x^2/f^*b$. Thus, if $h \le (b^2/f^*b)$, then the arch will be stable, but the hole will develop further when $h > (b^2/f^*b)$ until a sinkhole opens.

Frequent scanning to monitor changes in the arch is very important, but can have high costs when the survey area is large. Moreover, GPR is not capable of mapping deep soil cavities because of equipment limitations and the complicated geological conditions.

Monitoring of Triggering Factors

Following a geological survey and risk assessment, boreholes may be constructed in high risk locations to monitor changes in the groundwater through the karst conduit (Figure 3).

Determining the forecasting threshold is a key part of the method, and laboratory testing is the most common way. First, some undisturbed soil samples are obtained, and these are subjected to geotechnical pinhole tests (Lei et al, 2002) in the lab. If the hydraulic gradient in the laboratory tests is greater than in the field, seepage deformation will generate in the soil, and a karst collapse will open at the ground surface. However, the forecasting accuracy is very low by this method due to discrepancies in the structures and physical-mechanical properties of soil even in the same layer.



Figure 1. Ground penetrating radar image of a highway in Guilin, China and the idealized model of its balance arch.



Figure 2. The idealized GPR modeling of its balance arch (Protodyakonov, 1962). σ_{ν} is the natural vertical stress; τ is the natural horizontal stress; LOM is the arch; h is the height of the arch; b is the half span; f is the Protodyakonov (1962) coefficient; x and y are the coordinates of A on the arch LOM; Rv is the horizontal thrust at the top of arch; P is the thrust at the arch springing and T is horizontal component, N is vertical component.



Figure 3. Monitoring of groundwater pressure.



time of maximum anomaly

Figure 4. Relationship between timing of maximum anomalies and collapses.

To improve the forecasting accuracy, a new method based on the residual analysis of groundwater pressure was developed (Table1). The monitoring data is anomalous when it is outside the confidence belt. The forecasting is based on relationships between the time that anomalous monitoring data were recorded and the time of karst collapse (Table 2).

The data analysis shows that the times of the maximum, minimum and most anomalous values appearing and the time of the sinkholes opening have a linear correlation. The equation describing the relationship between the time of the maximum anomaly appearing and the time of the sinkhole opening was y=0.965x+1356, with a correlation coefficient was 0.998 (Figure 4). Similarly, the equation describing the relationship between the time of the minimum anomaly appearing and the time of the sinkhole opening was y=0.98x+776.5, with a correlation coefficient of 0.998. Finally, the equation describing the relationship between the time of the relationship between the time of the most anomalous

ID	The monitoring time	Monitoring data(kpa)	Simulating data(kpa)	residual errors
1	8/10/2007 15:55	21.061	22.3339	-0.12729
2	8/10/2007 16:00	21.078	22.3265	-0.12485
3	8/10/2007 16:05	21.078	22.3192	-0.12412
4	8/10/2007 16:10	21.103	22.3119	-0.12089
5	8/10/2007 16:15	21.111	22.3045	-0.11935
171333	10/1/200813:40	135.45	137.7855	-0.23355
171334	10/1/200814:00	135.69	137.7866	-0.20966
171335	10/1/200814:20	135.85	137.7877	-0.19377
171336	10/1/200814:40	135.88	137.7887	-0.19087
171337	10/1/200815:00	135.97	137.7898	-0.18198

Table 1. Monitoring simulation data and residual errors.

Time of sinkhole opening	Time of anomal <i>ies</i>	Number of anomalies	Minimum anomalies (k <i>pa)</i>	Time of minimum anomali <i>es</i>	Maximum Anomalies (kpa)	Time of maximum anomalies
	10/16/2007	175				
	10/26/2007	107	-1.6027	10/26/2007 4:15		
2007-10-28 18:00	10/28/2007	34			-1.221	10/28/2007 13:35
	10/29/2007	41			-0.017	10/29/2007 11:15
	11/2/2007	361	-0.0498	11/2/2007 8:42	Ì	
	11/3/2007	23			Ì	
2007-11-7 18:00	11/4/2007	186			Ì	
2007-11-8 22:00	11/8/2007	17	-0.1925	11/8/2007 10:00	-0.2419	11/8/2007 10:50
2007-11-9 22:00	11/9/2007	26	-0.2019	11/9/2007 5:35	0.16373	11/9/2007 5:15
	11/15/2007	52	-0.3254	11/15/2007 4:05		
2007-11-18 22:00	11/17/2007	84			-0.8697	11/17/2007 9:50
	7/7/2008	11	-0.0268	7/7/2008 12:00		
2008-7-11 11:00	7/11/2008	11			-0.0287	7/11/2008 10:40
	8/19/2008	72	-0.1403	8/19/2008 8:40	Ì	
2008-9-7 12:10	8/20/2008	43			-0.0806	8/20/2008 11:20
	9/11/2008	22			-1.2286	9/11/2008 1:20
	9/29/2008	31	-1.3046	9/29/2008 19:00		
2008-10-1 15:00	9/30/2008	5			1	

Table 2. Relationship between the timing of anomalous values and karst collapses in Guangzhou, China.

value appearing and the time of the sinkhole opening was y=1.043x-1707, with a correlation coefficient of 0.998. Consequently, the time of a sinkhole opening may be predicted when an anomalous value fits the equation following monitoring. The verification of this method will be very important in the future.

Strain measurement using optical fibers

Using optical fibers to forecast karst collapse is one of the newest technologies. It has been found that there is a linear relationship between the Brillouin frequency shift (BFS, described by $V_{\rm B}(\varepsilon,T)$) and the strain ε and the temperature T in the fiber optic sensor (Bao et al, 1995, Kurashima, 1993). The linear relationship can be expressed as:

$$V_B(\varepsilon,T) = V_B(0,T_0) + C_1 \varepsilon + C_2(T-T_0) \quad (\text{Eq } 1)$$

where: ε is the strain; T is temperature; $V_{\rm B}(\varepsilon, T)$ is the BFS including strain and temperature; $V_{\rm B}(\theta, T_{\theta})$ is the BFS at the initial temperature, T_{θ} without strain; and C_{1} and C_{2}

are the strain coefficient and the temperature coefficient, respectively. The feasibility of this linear relationship can be seen by the model test (Figure 5). First, optical fibers were laid in different soil layers. When the soil is damaged or changed, if the fiber can maintain the same strain changes as the soil, the strain changes in the fiber will show the changes in the soil, and thus can predict sinkhole opening at the surface.

The results show that the position of peak strain in the optical fibers corresponds to the area of disturbance and cavern formation in the soil, and the change in optical fiber strain in different soil layers indicates the vertical boundary of the area of disturbed soil (Figure 6). The time series of optical fiber strain shows the ongoing formation of areas of disturbed soil formation. In time, the Brillouin optical time-domain reflectometer (BOTDR) will become a reliable method for monitoring and predicting sinkhole collapse or subsidence, especially along linear infrastructure construction projects, such as highways and railways.



Figure 5. Model sinkhole tests using optical fibers in Guilin, China.

Discussion

Sinkholes are one of the main geological hazards in karst areas. They are very difficult to forecast due to their concealed nature and sudden appearance. Research from characterizing karst collapse formation and monitoring has identified some effective methods for predicting karst collapse, such as geophysical surveys, monitoring trigger factors, and strain measurements using optical fibers. However, some shortcomings exist for all these methods. Geophysical surveys for real time monitoring and forecasting karst collapse can have very high costs, and the precision and depth of the exploration are limited by equipment parameters and geological conditions. Integrating geophysical surveys with other methods to identify and explore sinkholes may provide better results.

When monitoring trigger factors using groundwater, it can be difficult to determine the threshold value, and the



Figure 6. Strain curve from optical fiber during sinkhole opening

location of the sinkhole opening cannot be determined. However, some measures such as the quantity and rate of groundwater withdrawal can be controlled by this method.

Using optical fibers to forecast karst collapse is a promising new technology. The position and time of sinkhole opening can be forecast by this method in theory. However, some key factors including the strain correlation between the optical fiber and the soil; the relationship between the optical fiber strain and the soil deformation; the effect of temperature on the optical fiber strain; and laying the optical fiber in undisturbed soil are not yet resolved. We firmly believe that, although immature, this method is very promising.

These observations above are provided in the hope that they will generate more public discussion.

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STATISTICAL ANALYSIS OF GPR AND SPT METHODS FOR SINKHOLE INVESTIGATION IN COVERED KARST TERRAIN, WEST-CENTRAL FLORIDA, USA

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Abstract

Sinkholes and sinkhole-related features in west-central Florida are commonly identified from surface penetration test (SPT) borings, which are located, in part, based on the results from ground penetrating radar (GPR) surveys. SPTs and GPR profiles yield complementary information-SPTs can indicate the presence of lowdensity soils or voids, while GPR profiles can resolve shallow stratigraphic indicators of subsidence. In GPR profiles collected at 103 residential sites in covered-karst terrain in west-central Florida, sinkhole-related anomalies were identified where GPR reflectors show downwarping, discontinuities, or sudden increases in amplitudes. We analyze the degree to which the shallow features imaged in GPR correlate spatially with the N-values (blow counts) derived from SPTs at 103 residential sites. Results are used to examine (1) which SPT indicators show the strongest correlations with GPR anomalies, (2) the degree to which GPR surveys improve the placement of SPT borings, and (3) what these results indicate about the structure of sinkholes at these sites. We find a statistically significant correlation between GPR anomalies and low SPT N-values with a confidence level of 90%. Logistic regression analysis shows that the strongest correlations are between GPR anomalies and SPT values measured in the depth range of 0-4.6 m. The probability of observing a GPR anomaly on a site will decrease by up to 84% as the minimum SPT value increases from 0 to 20. Boreholes drilled on GPR anomalies are statistically significantly more likely to show zones of anomalously low SPT values than boreholes drilled off GPR anomalies. The odds ratio depends on how the threshold criteria for low N-values are defined, with a maximum observed odds ratio of 2.89. Several statistical results suggest that raveling zones that connect voids to the surface may be inclined, so that shallow GPR anomalies are laterally offset from deeper zones of low N-values.

Introduction

Sinkholes are a common cause of damage to residential buildings and other infrastructure in the covered karst terrain of west-central Florida (e.g. Frank and Beck, 1991). Sinkhole activity can be manifested as recognizable topographic depressions that may evolve with time. However, identifying sinkhole potential in the absence of such surface subsidence features is a challenge.

Schmidt (2005) states that sinkhole investigations should be done in an integrated way that involves desk and site reconnaissance study, geophysical investigation, floor elevation mapping, geotechnical investigation and geological interpretation, laboratory analysis and structural analysis of the site. Standard penetration tests (SPTs) and cone penetration tests (CPTs) are the most common geotechnical field tests used in sinkhole investigation. SPTs are made by repeatedly vertically dropping a 63.5 kg hammer for 76.2cm length until a total penetration of 45cm is reached. The number of blows required to penetrate the last 30cm is called the N-value. The N-value, or blow count, is related to the density of granular soils or stiffness of cohesive soils. Zones with low N-values are expected in association with raveling into a sinkhole cavity or a dissolution cavity itself. However, Dobecki et al. (2006) have stated that blind drilling on sites would have low probability of intercepting a raveling zone and may instigate ground collapse incidents. Ground penetrating radar surveys are useful in identifying stratigraphic indicators of subsidence. These indicators include downwarping or, discontinuities in near-surface strata, or locally abrupt increases in GPR amplitudes. If borings were sited on GPR anomalies, the total number of borings could be minimized, decreasing total cost and minimizing unnecessary ground collapse incidents (Dobecki et al., 2006).

Neither ground penetrating radar nor SPTs are in themselves definitive measures of the presence of an active sinkhole (e.g. Schmidt, 2005). This argument has also been made by others, including Zisman (2001), who developed a scoring method for characterizing sinkhole potential of a site using geological and geotechnical factors. Zisman (2001) developed his criteria based on experience gained in west-central Florida.

By analyzing relationships between GPR-determined "sinkhole" anomalies and SPT records, we can address questions about the strengths and limitations of each method for detecting sinkholes. We can also test hypotheses about sinkhole structure. For our study sites in west-central Florida we examine (1) which characteristics of SPTs show the strongest correlation with the presence of GPR anomalies, (2) the degree to which GPR surveys improve the placement of SPT borings over random siting, and (3) what we can infer about the structure of sinkholes at these sites. To do this, we analyze GPR and geotechnical data collected from 103 residential sites in west-central Florida for which sinkhole activity was suspected (Figure 1). Across these sites a total of 299 SPTs were run (Figure 1), or about 3 per site. We find that using GPR data does increase efficiency in finding low N-value zones, and the effect is strongest for SPT values from shallow depths.

Study area

Most of the study area is characterized as lowland area, with Quaternary sediments overlying Tertiary carbonate rocks (Scott, 1988). Most of these sediments are unconsolidated sand, silty sand and sandy clay deposits that range in thickness from 0 to >60 meters (Figure 1). Other morphological features in the study area include plains, uplands, ridges and swamps. Carbonate rocks are exposed in places in west-central Florida (Florea, 2006) but not at any of the residential sites studied. At the study sites, the mean depth to groundwater was 2.6m, with a minimum depth of 0.46 meters.

Field Methods

Consistent methodology was used for ground penetrating radar surveys and geotechnical tests at the 103 residential sites shown in Figure 1. The GPR system works by emitting high frequency electromagnetic waves into the ground with a transmitting antenna and recording the reflected signals with a receiving antenna while both antennas are pulled across the ground. The



Figure 1. Study sites (red dots), soil type, and overburden thickness in west-central Florida. Capitalized labels show counties. GPR surveys and SPT borings were conducted at each study site. Soil types and overburden thickness from Sinclair et al. (1985). County boundaries from FDEP (2013). GPR profiles were collected by GeoView, Inc and SPT borings by Ground Down Engineering, Inc.

amplitude of the reflected signals is related to contrast in dielectric permittivity of subsurface materials. In this study, a Mala GPR system was used to collect ground penetrating radar (GPR) profiles, generally using a 3m grid spacing. The data were collected using 250MHz and 500MHz antennas for internal and external parts of residential sites respectively. The depth of penetration for GPR surveys is usually less than 12.2m. The bedrock depth for the study area ranges from 0 to 31.5 m with a mean depth of 13.1 m. Hence, GPR surveys rarely if ever image subsurface cavities. This is related to the penetration limitation and to the fact that the underlying cavity may not be directly below the site or survey lines. However, sites affected by sinkholes may have raveling activity at depth which may result in downward migration of granular sediments from the shallow soil layers. This movement can make near surface granular soils less dense and result in downward deformation of cohesive layers. These processes result in recognizable features in the radar images, if they are within the range of penetration of the GPR signal. These associated

features, recognized as locally downwarping layers, lateral discontinuities, and abrupt increases in amplitude, were subjectively identified from the GPR images. Areas encompassing anomalous sections of GPR transections were then delineated.

GPR surveys were followed by geotechnical field investigations, including drilling, soil sampling, laboratory analysis and insitu field tests. A minimum of three boreholes were drilled in 95% of the sites. Borehole sites were chosen to include both areas within and outside of GPR anomalies. The average depth of boreholes was 17.4m. Standard penetration tests (SPT) were conducted in all boreholes. SPTs were usually started at 1.8m depth and continued downward at 1.5m intervals below a depth of 3m.

A number of methods exist to characterize the strength of soil based on SPT values (e.g. Carter et al., 1989). Following Meyerhof (1956) and Peck et al. (1974), granular soils are considered loose if they have an N-value less than 10 and are considered dense if they have N-value above 30.

Statistical Analyses: Results and Discussion

Because both SPT results and GPR anomalies are indirect and imperfect indicators of sinkhole processes, we can use neither as a direct proxy for the presence of a sinkhole. Thus it is valid to examine SPT data as a predictor of GPR anomalies, or vice-versa. Here we do both, but we use different statistical methods because we are addressing different questions with each analysis.

The SPT data contain a range of values (N-values) that vary as a function of depth at each boring location, at intervals of ~1.5 meters. In contrast the GPR data are categorical data, either "yes" an anomaly is defined at the given location, or "no", no anomaly is observed at that point. SPT data from 0-12.2 meters depth are analyzed, so as many as 9 N-values are considered per SPT site. These measurements typically span transitions between surficial sands to silty sands. At some sites clays are encountered. To examine at least indirectly the role of the stratigraphy in the SPT readings, the SPT records are divided into three depth zones, as shown in Figure 2. For the analysis below, data were treated with ArcGIS 10.1, AutoCAD 2010, and SAS 9.2 software, and using codes written in Perl and Matlab R2010a.



Figure 2. SPT zones defined for use in the statistical analysis. For each boring, the average N-value and the minimum N-value are found for each of the three depth ranges.

SPT values as predictors of GPR anomalies

Binary logistic regression is a method for describing the relationship between an independent variable that can take on a range of values (e.g. SPT) and a "yes or no" categorical dependent variable (e.g. GPR anomaly). This method was applied to the entire data set of 299 SPTs. Six categories of SPT criteria were defined: the minimum SPT value observed in each of the three depth zones, and the average SPT value observed in each of the three depth zones (Table 1). For each of these six criteria, the probability of encountering a GPR anomaly at the SPT site was computed as a function of the SPT criteria value.

If there were a perfect SPT threshold predictor of the presence of a GPR anomaly, SPT values lower than the specific threshold would be 100% correlated with the presence of a GPR anomaly, and the probability of a

SPT criteria	Description	Assumed threshold N-value for sinkhole potential used in odds ratio analysis
ShallowA	Average SPT value over the depth range 0-4.6 m	Average SPT < 10
ShallowM	Minimum SPT value over the depth range 0-4.6 m	Minimum SPT< 4
IntermediateA	Average SPT value over the depth range 3.1-7.6 m	Average SPT < 15
IntermediateM	Minimum SPT value over the depth range 3.1-7.6 m	Minimum SPT< 4
DeepA	Average SPT value over the depth range 4.6-12.2 m	Average SPT < 20
DeepM	Minimum SPT value over the depth range 4.6-12.2 m	Minimum SPT< 5

Table 1. SPT criteria used in statistical analyses for Figure 3, Table 2, and Table 4.

GPR anomaly would be 1 for all SPT values below the threshold criteria. The probability would then decrease abruptly to zero at the threshold SPT value and remain at zero for higher SPT values. Thus in Figure 3, the sharper the plunge in the probability curve, the better the predictive capability of that variable for associated GPR anomalies. Figure 3 shows that sites with no low SPT values, i.e. those with high minimum SPT values, indeed have a low probability of showing a GPR anomaly. The figure also shows that SPTs with the lowest minimum values have ~60-70% probability of correctly predicting the presence of a GPR anomaly.

Figure 3 shows the probability of a coincident GPR anomaly for 5 of the 6 SPT criteria. (The 6th criteria did not satisfy the confidence level described below.)

Figure 3 shows that as the minimum SPT value in the shallow zone (0-4.6 m) ranges from 0 (very loose soil) to 20 (compact soil), the probability of finding a GPR anomaly will decrease by 84% (from 70% to 11%). Minimum SPT values in the intermediate zone are less good predictors of GPR anomalies: from minimum values of 0 to 20 the probability of a coincident GPR anomaly drops by 68% (from 59% to 19%). Minimum SPT values in the deep zone show the weakest correlation: from 0 to 20 the probability drops by only 23% (from 55% to 42%).

For each of the six categories in Table 1, the model fit statistics are tested with Wald chi-square analysis (Table 2). The confidence level is set to 90%, and results are shown only where there is at least a 90% confidence level of rejecting the null hypothesis of zero logistic regression coefficient. (A coefficient of 0 would correspond to a flat line across Figure 3.) 90% confidence corresponds to a P-value of 0.10 or less in the third column of Table 2. The SPT criteria for the shallow zones show much

lower P-values than for intermediate and deeper zones in general. This implies that SPT criteria from shallow zones are better predictors of the presence of a GPR anomaly.

The imperfect correlations between SPT values and GPR anomalies could be explained by a variety of phenomena. In cases where low N-values are present without corresponding GPR anomalies, possible explanations include (a) partially saturated unconsolidated sediment may be naturally loose without being disturbed by sinkhole activity; (b) GPR surveys may not be effective at imaging some sinkhole-related anomalies due to poor penetration in the presence of a shallow clay layer or



Figure 3. Logistic regression results for the 5 SPT categories (Table 1) that satisfy the 90% confidence level criteria. The horizontal axis shows the average of or minimum N-value over the defined depth range. The vertical axis shows the probability of observing a GPR anomaly coincident with the SPT location. Zero correlation would appear as a horizontal line. A perfect SPT threshold criterion would appear as a vertical line that would drop from 1 to 0 at the threshold N-value.

Table 2. Model fit statistics for logistic regression

 shown in Figure 3. *=not significant at 90% confidence.

Model fit test							
SPT Criteria	Wald Chi- Square	P-value					
ShallowM	11.18	< 0.01					
IntermediateM	8.19	< 0.01					
DeepM	2.64	0.10					
ShallowA	12.42	< 0.01					
IntermediateA	2.66	0.10					
DeepA	0.58	0.45*					

absence of shallow reflectors; or (c) there may be no near-surface anomalies over a growing void, as in the case of cover-collapse sinkholes (e.g. Tihansky, 1999).

Conversely, cases where GPR anomalies are recorded but without underlying low SPT N-values could be attributed to (a) GPR anomalies that represent features of sinkholes that are no longer active; or (b) active sinkholes with shallow cohesive soil layers that gradually deform downward as one unit without disturbing its overall stiffness or density. Finally, one phenomenon that could explain both cases is simply a scenario in which GPR anomalies and low SPT N-values associated with a common sinkhole are nevertheless spatially offset from each other. For example, material migrating into a cavity may migrate laterally or along an inclined path, contrary to the simple assumption of a vertical path.

GPR anomalies as predictors of low N-value SPT results

To assess the degree to which GPR surveys improve the odds of locating boreholes with low N-value SPTs requires an analysis with GPR anomalies as the independent variable. One applicable statistical method is odds ratio (OR) analysis.

The odds ratio is simply the ratio of the probability of observing a low SPT value on boreholes drilled on GPR anomalies to those drilled outside GPR anomalies. An odds ratio of 1 indicates that the odds of finding a low SPT are equal for boreholes drilled inside and outside GPR anomalies. An odds ratio greater than 1 indicates that the odds of finding a low SPT value are higher for boreholes drilled on GPR anomalies. To compute an odds ratio requires that we define "low SPT value", as well as "on GPR anomaly" vs. "outside GPR anomaly". For this purpose, the six SPT criteria of Table 1 are used, and four GPR group classifications are defined as in Table 3. To use odds ratio analysis a threshold SPT value must be defined; if the SPT criteria falls below this threshold value, then the SPT is considered "low". The threshold values are listed in Table 1. For example, when the SPT criteria is the average value over the shallow zone (0-4.6 m), this average N-value must fall beneath 10 to be called "low" SPT (first line of Table 1).

The threshold criteria were defined using a two-step procedure. First, an optimization code searched for the threshold that showed the strongest correlation between the GPR and SPT results for the entire 103-site data set. The threshold values were then subjectively shifted slightly to values that hold geological significance in order to facilitate comparison with other studies. For example, an optimal threshold N-value of less than 4 was shifted to 4, which corresponds to a commonly used definition for "very low" N-value (Terzaghi and Peck, 1948).

The presence or absence of GPR anomalies can be defined for residential sites or for individual boreholes. Table 3 shows the four GPR group classifications described here. For each of the GPR group classifications, the odds ratios were computed for the six SPT criteria. The results are shown in Table 4. For inclusion in Table 4, we require that the null hypothesis (an odds ratio of 1) can be rejected at the confidence level of 90%. (This corresponds to P-values less than 0.1 in Table 4.)

Table 4 shows that regardless of the GPR anomaly group classification, using GPR anomalies to locate boreholes improves the odds of finding low minimum SPT values in the shallow and intermediate depth zones, in effect from 0 to 7.6 meters. ("Low" is defined as a minimum N-value less than 4 for both depth zones.) We note that in most cases the odds ratios computed using minimum SPT N-value criteria are higher than corresponding odd ratios using average SPT N-value. The odd ratios are also generally highest for shallow zones, lower for intermediate zones, and lowest or statistically insignificant for the deep zones. The overall highest odds ratios are found when GPR anomaly classification is made using group 4 (Table 4).

Several aspects of this statistical analyses support the hypothesis that GPR anomalies may be associated with, but laterally offset from low SPT borings. Odds ratios for group 2 classification are lower than for

	1		l.
GPR GROUP	Residential sites with at least one GPR a	Residential sites with no GPR anomalies	
	Boreholes drilled on GPR anomalies	Boreholes drilled outside GPR anomalies	Boreholes drilled outside GPR anomalies
Group 1	Boreholes drilled on residential sites with GPR anomalies		Boreholes drilled on residential sites with no GPR anomalies
Group 2	Boreholes drilled on GPR anomalies	Boreholes drilled outside G	PR anomalies
Group 3	Boreholes located on sites with GPR anomalies and drilled inside the GPR anomalies	Boreholes located on sites with GPR anomalies but drilled outside the GPR anomalies	
Group 4	Boreholes located on sites with GPR anomalies and drilled inside the GPR anomalies		Boreholes drilled on residential sites with no GPR anomalies

Table 3. Classifications for spatial correlation between SPTs and GPR anomalies.

Table 4. Odds ratio analysis results for SPT categories with ratios significantly different from 1. The odds ratio is the ratio of the probability of observing a SPT value below the threshold on boreholes drilled on GPR anomalies to that for boreholes drilled outside GPR anomalies An odds ratio >1 implies that GPR data "add value", in that SPTs on GPR anomalies are more likely to encounter zones with N-values below the threshold.

Data Group	SPT Criteria	SPT Zone	Depth Range (m)	SPT Threshold value	Odds Ratio for ob- serving SPT below threshold based on GPR anomaly	P-value
Group 1	Average	Shallow	0-4.6	10	2.22	0.0001
	Minimum	Shallow	0-4.6	4	2.27	0.0001
		Intermediate	3.1-7.6	4	1.63	0.0156
Group2	Average	Shallow	0-4.6	10	2.00	0.0017
		Intermediate	3.1-7.6	15	1.76	0.0064
	Minimum	Shallow	0-4.6	4	2.63	0.0001
		Intermediate	3.1-7.6	4	1.39	0.0376
Group 3	Average	Shallow	0-4.6	10	1.41	0.0641
		Intermediate	3.1-7.6	15	1.84	0.0147
		Deep	4.6-12.2	20	1.95	0.107
	Minimum	Shallow	0-4.6	4	1.77	0.0188
		Intermediate	3.1-7.6	4	2.24	0.0062
		Deep	4.6-12.2	5	1.35	0.0709
Group 4	Average	Shallow	0-4.6	10	2.57	0.0001
		Intermediate	3.1-7.6	15	1.70	0.0159
	Minimum	Shallow	0-4.6	4	2.89	0.0001
		Intermediate	3.1-7.6	4	2.35	0.0019

group 4. Group 2 compares all boreholes drilled on GPR anomalies against all boreholes drilled outside GPR anomalies, irrespective of the presence of other possible GPR anomalies at a given residential site. In contrast group 4 classifications compares boreholes drilled on GPR anomalies against only boreholes drilled on residential sites with no GPR anomalies. This latter grouping (group 4) excludes boreholes drilled outside GPR anomalies but located in residential sites with GPR anomalies. The higher odds ratio for group 4 suggests that on sites with GPR anomalies, nearby boreholes are more likely to encounter low N-values.

Another result supporting the above hypothesis is the observation that minimum N-value criteria show better correlation with GPR anomalies than average N-value criteria, for both logistic regression analysis and odds ratio analysis. This suggests that sinkhole-related low N-values zones are thinner than the extent of the defined depth zones (0-4.6 m or 3.1-7.6 m). If cavities were vertically below GPR anomalies, one should expect consistently low N-values in all zones of a vertical borehole. So a given vertical borehole may only encounter a portion of an inclined disturbed low N-value zone.

Finally, a third result supports the hypothesis that inclined zones of low N-values terminate at GPR anomalies at the surface. Minimum N-value criteria for shallow depths (0-4.6 m) show stronger correlation with the presence of GPR anomalies than the criteria for intermediate depths (3.1-7.6 m). N-values at deepest depth ranges (4.6-12.2 m) show the weakest or insignificant correlations. These are observed in both the logistic regression and odd ratio measures.

Conclusions

Sinkhole related features identified on GPR images and SPT values within three depth ranges were used to examine relationships between GPR anomalies and SPT N-values at 103 residential sites in west-central Florida. Logistic regression analysis was used to examine SPT values as an indicator of sinkhole-related GPR anomalies, and odd ratios were computed for GPR anomalies as predictors of low SPT values. Both methods show statistically significant correlations between GPR anomalies and zones of low SPT N-values at depth ranges of 0-4.6 m and 3.1-7.6 m. Both methods show the strength of the correlation decreases with depth. The strongest correlations are observed when low-SPT threshold criteria are based on minimum SPT values rather than average SPT values over a given depth range. Taken together, these observations suggest that raveling zones that connect voids to the surface may be inclined, such that shallow GPR anomalies are laterally offset from deeper zones of low N-values. Future analysis of this data set will seek to account for the effects of soil type, shallow clay layers, overburden sediment thickness, geology, and geomorphology on the correlation between sinkhole-related GPR anomalies and SPT values.

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INTEGRATED GEOPHYSICAL METHODS FOR GROUNDWATER EXPLORATION IN A KARST AREA WITH OR WITHOUT THIN COVER — A CASE STUDY FROM TAI'AN CITY, SHANDONG PROVINCE, CHINA

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Abstract

Because of heterogeneity and anisotropy, it is very difficult to optimize groundwater exploration drilling locations in karst areas using only hydrogeological information. However, the integrated application of the audio frequency telluric method and electrical resistivity tomography has proved to be efficient for groundwater exploration in karst areas with or without thin cover. In the case studies presented here, audio frequency telluric profiling is used to roughly determine the location and strike of a karsted or fractured zone where the cover thickness is less than 30 m, then an electrical resistivity profile perpendicular to the strike of the zone is designed to reconstruct the resistivity structure with a Schlumberger array. By combining the geophysical results with available hydrogeological data, an optimal drilling site can be established. This integrated geophysical approach for karst water exploration has been used in several projects and the results show that the method is reasonable and useful.

Introduction

Since 2009, extreme climate events, persistent drought and low rainfall, has made drinking water scarce for human consumption and agricultural purposes in some parts of China, especially in karst regions. At the beginning of 2012, a groundwater exploration team was constituted by the Institute of Karst Geology to support drought disaster relief. The team traveled to Tai'an city, Shandong Province, in the east of China (Figure 1) to search for promising exploratory sites for karst water using hydrogeological investigations and geophysical prospecting. Within a month, 23 exploratory wells were optimally positioned and drilled. Subsequently, 21 were tested by pumping, and produced an abundance of water.

Because of the highly non-uniform development of karst environments, suitable geophysical methods needed to be selected to identify water-bearing structures such as waterfilled caves or water-filled fissures underground. Recently, the audio frequency telluric method (AFTM) has been successfully employed to detect water in karst settings (Chen, 1988; CGS 2005; Gan, 2011), and to probe fissures of water in combination with the induced polarization (IP) method (Li, 2009). The typical advantages of this method are that they are both rapid and cost-effective; however, this is countered by disadvantages, including a shallow investigation depth and a lack of anomaly variations with depth. Electrical resistivity tomography (ERT) can be applied to define the water table (Zaidi, 2012), to delineate aquifers (Kumar, 2012), to search for karst geological structures (Leuccim, 2005) and find karst water (Metwaly, 2012; Vlahović, 2011) using characteristics of the resistivity variation with depth. Compared with using a single geophysical method alone, the integrated approach usually provides more reliable information, and as a result has been widely applied for groundwater investigations. Alexopoulos (2011) employed both the very low frequency (VLF) electromagnetic method and ERT to map water pathways. Vargemezis (2011) even carried out VLF, Self-Potential (SP) and ERT surveys together to optimize locations for the construction of hydro wells.

Two examples presented here to trace karst water show that the AFTM and the ERT methods have the advantages of saving time and increasing efficiency.

Geophysical methods Audio frequency telluric method (AFTM)

This method, which takes advantage of natural telluric current variations with frequencies induced in the earth by phenomena such as solar emission and thunderstorms, detects conductive difference distributions underground and interprets them in terms of geology or hydrogeology.

The AFTM is a preferred method for rapid ground reconnaissance and shallow exploration where





overburden thickness is usually less than 30 m, It is conducted in situ to determine potential gradient measurements along a line, which is usually set up perpendicular to the strike of geological structures. The equipment used to measure the potential gradients was a Model YDD-B unit, with frequency range of 20 Hz to 25 kHz, manufactured by the Center for Hydrogeology and Environmental Geology Surveying. Measurement stations were usually 10 m apart. Because telluric currents change with time, the potential gradient between two electrodes, induced by a telluric current field, is unstable. Thus the profile measurements needed to be collected as quickly as possible in the field (generally within an hour). In the end, the potential gradient was plotted against the midpoint of the potential electrodes. This method is often used to map shallow subsurface karst features showing relatively low potential values if they are water-filled.

Electric Resistivity Tomography (ERT)

For the ERT survey, a 60-channel WGMD-3 unit (manufactured by Chongqing Benteng Digital Control Technical Institute, China), in a multi-electrode configuration, was used.

Apparent resistivity data were collected and stored automatically using 60 electrodes with a 10 m spacing. A Schlumberger electrode configuration was selected because of its suitability for the study of horizontal and vertical structures.

The results are produced using Res2dinv software, which first creates an underground resistivity model and then calculates resistivity and depth values for geological structures detected along the profile. The maximum investigation depth mainly depends on the total length of the spread.

Case study 1 Geological setting

The survey site at 36°08'12"N, 117°18'05"E is located at Guanlu village, about 20 km east of Tai'an City in Shangdong Province, China. The widely distributed overburden in the region, with a thickness of about 10 m, consists of Quaternary deposits of sand and gravel. The underlying karst water-bearing rock groups, with beds dipping N25°W at an angle of 7°, consist of Gushan Fm. (C3g) (upper Cambrian) limestone and thin- to thick-bedded limestone or argillaceous limestone embedded within the shale of the Zhangxia Fm. (C2z) (middle Cambrian), as shown in Figure 2.

The terrain in the study area is flat. The Wen River, flowing eastward about 600 m to the north, coincides with the lowest drainage datum plane. Groundwater moves from south to north following two discharge mechanisms. The first involves groundwater moving along rock layers with scattering discharge as a result of the shallow incision of the valley, the low hydraulic gradient of groundwater, and the wide areal distribution of the groundwater. The second involves abundant volumes of groundwater moving within karst fissures with centralized discharge. The condition of the landforms favors groundwater accumulation. The majority of the karst areas in the south provide stable sources of groundwater supply. However, one disadvantage is that contaminated water may intrude into the system from the Wen River as a result of the extraction of karst groundwater.

Regional tectonic structures trend from northwest to southeast. Those structures, influenced tectonically and



Geophysical methods

The five geophysical survey lines shown in Figure 2 were mainly set up perpendicular to water-bearing structures that are oriented south-north or northwest-southeast. The AFTM was first used to detect the horizontal trend of zones of lower potential and then the ERT method was used to vertically probe lower resistivity variations with depth.

The potential curve of the AFTM for line 5 in Figure 3 shows a clear lower potential anomaly at stations 350-470, possibly indicating the existence of karst fissures somewhere underground.

In the end, the regions of lowest potential from all profiles in the AFTM could be identified (see Figure 3), for example, stations 130/1-170/1, 200/1-220/1, 90/3-150/3, 160/3-190/3, 95/2-205/2 and 120/4-200/4. The two main branches of the low potential anomalies in lines 1 and 3 extend southward and meet at lines 2 and 5, showing a Y-like shape that is narrow in the north and wide in the south. These lower potential anomaly zones, because of their wider distribution, are inferred to be karst fissures with an abundance of water.



Figure 2. Hydrogeological map of survey site and geophysical profiles (1. Survey site, 2. Surface water direction, 3. Drill hole, 4. Fault, 5. Quaternary, 6-10. Cambrian Limestone, 11. Recommended borehole, 12. Fracture zone, 13. Profile direction, 14. Station/profile No., 15. Dip direction and dip).



Figure 3. Potential curves of the AFTM for lines 1, 2, 3, 4 and 5.

Subsequently, the ERT line was set up along the strike of the lower potential anomaly. In Figure 4 (upper), Schlumberger array apparent resistivity contours, taken from the ERT for line 5, show a clear contact between lower and higher resistivity zones at station 500/5. In particular, the striped low resistivity zone between stations 380/5 and 500/5 reveals vertical karst fissures.

The stratigraphy of the proposed drill hole at station 440/5 in Figure 4 (lower) was predicted from the Schlumberger resistivity section in the ERT to consist of a subsoil of alluvial clay, sand and gravel that is about 26 m thick. Karst fissures and caves were interpreted at depth ranges 26 - 70 m and 90 - 110 m, respectively.

These predictions were tested by hammer drilling. The resulting well is 150 m deep, with a static water level 10 m below the surface. The first cave appeared at a depth of 32 m. Hammer drilling was difficult due to the highly fractured nature of the rock that caused the pipe to stick often. After pumping tests, the pumping capacity was set at 480 m³/d with a maximum drawdown of 20 m.

Case study 2 Geological setting

The study site at 36°09'31"N, 116°53'02"E is located at Momoshan village, approximately 20 km west of Tai'an City. The region is characterized by cone karst and valley topography. The maximum elevation difference in the region is about 150 m and the valley is about 300 m wide. Geophysical survey lines, positioned with only small changes in elevation, are located across a hill slope showing bare karst rocks. The overburden thickness varies from 0-5 m, and has a monoclinal structure with beds dipping N20°W at angles of 10° to 20°. The underlying rocks are thin argillaceous limestones or edgewise limestones embedded with thin shale (upper Cambrian). Karst fissures, 0.1-2 cm wide and up to 2 m long, are widely distributed on the ground surface. Groundwater moves from north to south in a direction that is nearly opposite to the dip direction of the beds. A map of the hydrogeology is shown in Figure 5.

Hydrological conditions, including a deep water table at a depth of about 100 m and the location of the survey on the southern side of the watershed, make it difficult to search for groundwater resources. Since 1949, three dry wells have been drilled nearby. From a landform perspective, high in the north and low in the south, it is likely that groundwater in this region moves southward along karst fracture zones in a concentrated flow regime. Therefore, appropriate geophysical methods can be chosen to outline these favorable zones.

Geophysical methods

As before, the AFTM was first conducted to roughly constrain the position and orientation of groundwater runoff zones, then the ERT method was applied to develop information on the water table and karstification level. The geophysical field setup is illustrated in Figure 5. The zone of lower potential anomaly is about 30 m wide, extending from the northwest to the southeast as constrained by lines 2, 3 and 4 in the AFTM (see Figure 6). Because of site limitations, only one ERT line could be arranged striking N65°E. Schlumberger array resistivity contours in Figure 7 (upper) readily show the lower resistivity anomalies (less than 300 Ω m) extending over a width of about 30 m and in a vertical band between stations 560/1 and 620/1.

Regions of lower resistivity determined by the integrated geophysical methods, and striking approximately 110°, were inferred to be karst fissures that could constitute favorable well positions. Because of site limitations, the testing drill hole was moved to station 570/2 based on the similar characteristics of the anomaly there.



Figure 4. Resistivity imaging (upper), Geological interpretation for profile 5 (lower) 1. Fine sand with gravel, 2. Gravel with fine sand, 3. Limestone, 4. Karst fissures, 5. Interbedded limestone and shale.





Figure 6. Potential curves of the AFTM for lines 2, 3, and 4.

The well depth is 190 m with a static water level at a depth of about 80 m. After pumping tests, the yield was determined to be 280 m³/d with a maximum drawdown of 40 m. The flow comes mainly from units at depths of about 127 and 161 m.

Conclusions

Many projects involving the search for groundwater in karst areas – with or without thin cover (< 30 m) – have shown that an integration of AFTM and ERT to optimize data acquisition and provide crosschecks can produce promising results. Fieldwork procedures usually consist of the following steps.

- First, more than three AFTM profiles are collected – primarily to roughly establish the strike of karst fractures or rapidly define the contact between non-soluble and soluble rock that may focus karst development and result in favorable drilling locations. However, accurate depth estimates are not generally possible with this procedure alone.
- 2. Second, to constrain the geometry of horizontal and vertical geological structures, ERT data with a Schlumberger array configuration are collected. In the survey, profiles are aligned perpendicular to the previously identified low potential anomalies, thereby enabling the detailed interpretation of karst geological structures by using information about resistivity variations with depth. For a Schlumberger array consisting of 60 electrodes spaced at 10 m, the maximum depth of penetration is about 150 m.



Figure 7. Resistivity imaging (upper), Geological interpretation for line 1 (lower) 1. Clay, 2. Limestone, 3. Karst fissures, 4. Interbedded limestone and shale.

The two methods taken together constrain lower potentials distributed horizontally (along strike) and similar changes in resistivity varying vertically. When combined with hydrogeological information, this procedure provides important and effective geophysical indications of the geological setting, and enables the optimal determination of well positions.

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EXAMPLES OF ANTHROPOGENIC SINKHOLES IN SICILY AND COMPARISON WITH SIMILAR PHENOMENA IN SOUTHERN ITALY

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Abstract

Anthropogenic sinkholes affect several built-up areas of Sicily (southern Italy) representing a great risk to people, buildings, and infrastructures. These phenomena are generally associated with the presence of ancient underground quarries for the extraction of calcarenite rock, used for building or ornamental materials. These quarries were poorly constructed and abandoned throughout history.

Field surveys, structural analysis of the fissure networks in the rock mass, and numerical modeling were carried out in order to understand the most significant factors responsible of the instability processes of underground quarries. The genetic mechanisms of anthropogenic sinkholes have also been investigated. Jointing and saturation conditions of the calcarenite, along with indiscriminate enlargement of voids, can reduce the available strength. This strength is needed to maintain the stability of the rock mass above the underground quarry, the lack of which can cause the sinkholes formation.

Finally, a comparison between the cases of Sicily and Apulia regions, where similar anthropogenic sinkholes are widespread, was carried.

Introduction

Anthropogenic sinkholes and subsidence phenomena are very widespread and generally linked to the presence of man-made caves, such as quarries and mines, or due to indiscriminate extraction of fluids including water, oil, and gas (Waltham, 2002; Waltham *et al.*, 2005). Many built-up areas of Sicily (southern Italy) are affected by such type of risk. In particular, Marsala (western end of Sicily, Figure 1) was affected in the past decades by several collapse phenomena which caused extensive damage to infrastructures and population. These phenomena are related to the presence of underground quarries for the extraction of calcarenites used as building materials.

These cavities are carved at depth varying from several meters to roughly 25 m on a single or superimposed layer, following the excavation techniques of chambers and passages separated by rock pillars. However, excavation typically occurred without any planning.

With time, the underground quarries were progressively abandoned for several reasons (i.e., interaction with the percolating waters, decay of the physical-mechanical properties of the rock, high costs, difficulties and risk excavation work).

Nowadays in many cavities signs of instability can be clearly recognized along ceilings, walls and pillars. These instabilities easily propagate upwards causing sinkhole and subsidence phenomena according to the mechanisms described in Parise & Lollino (2011), thus creating consistent damages to buildings and infrastructures.

A sinkhole, occurred in June 2011 and related to an underground quarry in the eastern sector of Marsala, is described in this paper as a case study (Figure 2). The site was selected for the availability of topographic data of the underground quarry, prior to the formation of the



Figure 1. Planimetric view of the studied underground quarry. In the inset, location of the Marsala area.

sinkhole, which were useful for defining the genetic mechanisms of this depression. The quarry was surveyed in 2000. During this survey various signs of instability, such as open fractures and detachment of large blocks, were observed on the vaults and at the pillars. After the June 2011 sinkhole, new surveys were conducted inside the quarry aimed at collecting additional data to better understand the factors that have played a role in generating the sinkhole (Figure 2).

Since the collapse occluded many of the remaining rooms, the 2011 surveys were limited to the western sector of the quarry (Figures 1 and 3A). Detailed surface topographic surveys were conducted in the following months to detect new signs of collapse or movements of the topographic surface.

In this article, we intend to describe the geological and structural features of the site study, and illustrate the preliminary results about the genesis of sinkholes obtained using finite element analyses. The numerical modeling was implemented following a similar procedure applied in other site studies in southern Italy (Parise & Lollino, 2011; Parise, 2012; Lollino *et al.*, 2013). Finally, a comparison between the cases of Sicily and similar anthropogenic sinkholes of Apulia region was made, in order to gain a better understanding of the mechanisms causing the sinkholes.

Geological setting

In the Marsala area Lower Pleistocene calcarenites, defined as "Calcarenite di Marsala" (Ruggieri & Unti, 1974; Ruggieri *et al.*, 1975) and referred to the Marsala syntheme, crop out (Di Maggio *et al.*, 2009). They are formed by three main lithofacies with vertical and lateral passages: a) coarse to fine yellow bio- and lithoclastic calcarenites, rich in macrofossils; b) sands; and c) gray sandy clays. Both b and c types are rich in microfossils. The calcarenites and the sands show a gradual lateral transition to sandy clays and silts which generally can be found at the base of the entire sequence.



Figure 2. The sinkhole formed in June 2011, in correspondence of the quarry in Figure 1.

According to Ruggieri et al. (1975) and Arces et al. (2000), the calcarenitic lithofacies can be divided into three lithotypes: i) coarse calcarenites and calcirudites strata, from 10 to 100 cm thick; ii) fine to coarse calcarenites with thickened grains; iii) medium to coarse calcarenites in irregular strata with intercalations of thin beds of silt. Usually the ii) type was carved in the quarries. The overall succession, at least 80 m-thick, gently dips (5-10°) towards the south and the southwest. The calcarenites are affected by intense high-angle fracture systems showing NW-SE and, subordinately, E-W direction (Figure 4A). In some locations, the Marsala Calcarenite is covered by Middle and Upper Pleistocene marine terraced deposits. In the underground quarry, chosen as a study case, the mining activity involved exclusively the fine to coarse calcarenites.

The sinkhole and the underground quarry

In June 2011 a sinkhole occurred in correspondence of an underground quarry, damaging several constructions, including a recreation centre and the



Figure 3. Sinkhole formed in June 2011. A: Breakdown deposits within the quarry in the proximity of the area affected by the sinkhole. B: Damage caused by the sinkhole to the overlying buildings.

nearby infrastructures (Figures 2 and 3B). A detailed topographic survey was conducted in order to define the perimeter, shape and depth of the sinkhole.

The survey was carried out using a topographic station, measuring at points with a grid spacing of 2.5 m, because of the presence of thick vegetation and the pronounced topography (Figure 7).

The sinkhole has an elliptical shape with a maximum diameter of 130 m, a minimum of 90 m and a maximum depth of 2.4 m. It is asymmetric with the deepest point located in the eastern sector, characterized by a 2 m-high scarp and a direction of elongation (NW-SE) parallel to both the underground galleries and the main tectonic discontinuities of the area.

During the months following the formation of the sinkhole a total of 4 survey campaigns were performed in order to evaluate the likely progressive evolution at



Figure 4. Stereographic projection (Schmidt, lower hemisphere) of the poles of the fracture plans in the calcarenite rock mass, as from the survey within the quarry (data elaboration by means of Daisy 3; Salvini, 2011). B: Main development directions of the underground passages.

the site. These measurements, performed along a crosssection (E-W) in the southern flank of the sinkhole, did not show any consistent variation of the topographic level (Figure 3B).

The underlying quarry consists of a series of rooms with quadrangular shape, in most cases connected and/or separated by thin rock walls or pillars. NW-SE oriented galleries, separated by thin rock walls, are present in the central sector of the quarry (Figures 1 and 4B).

The room size is highly variable: the average height is 2.7 m, ranging between 1.1 and 7.5 m.; the average width is roughly 3.5 m (1.8 - 8 m); the average length is 12 m(2.6 - 40 m). The walls are 20 cm to 4 m thick, whilst the pillars have a width varying from 30 cm to 4 m, and a length between 70 cm and 6 m. Overall, the quarry is 480 m long, with overburden varying from 8.2 to 11.8 m. The calcarenite was extracted along variable directions. The pattern of the quarry is mainly influenced by the quality of the rock and the perimeter of the land properties. Shape and distributions of the rooms display very different directions in the western sector of the quarry. The central and eastern sector of the quarry, instead, show preferential excavation direction as inferred by the presence of rooms and galleries tens of meters long and with direction (NW-SE) parallel to the main rock discontinuities (Figure 4). The enlargement of the quarry following the principal discontinuity directions was necessary to extract entire blocks of calcarenite.

Instability phenomena inside the quarry

Inside the quarry, signs of instability at different stages of evolution are visible along the ceilings, the walls and the pillars.

Instabilities are generally due to the fracture system of the calcarenite body, the dense and irregular distribution of rooms and galleries, and the rock alteration caused by water infiltration. Sub-vertical fractures, and fracture parallel or coincident with the bedding planes caused detachment of large volumes of rock from the vaults (Figure 5).

According to the 2000 survey, falls were mainly located in the eastern sector of the quarry where rooms are larger and separated by small rock pillars and walls, only 30 cm thick. In this sector, movements of large portions of rocks following the sub-vertical fractures were also detected, in addition to falls. This sector is located in the area where the sinkhole occurred. Along these fractures, saturation and chemical alteration due to the percolating water are visible. The walls are affected by a joint system parallel to the walls, with presence of both incipient fractures and tensile joints with aperture of several centimeters.

Two types of fractures can be recognized: fractures preexistent to excavation of the quarry, and fractures caused by the local instability of rocks inside the quarry.

The first type of fractures are continuous along the ceilings of different rooms, and are mainly tensile fractures with visible signs of rock alteration due to the water circulation. In the second type, along the



Figure 5. Instability phenomena in the quarry vaults. Falls (photo A) and movements of large volumes of rock along sub-vertical fractures (photo B) surveyed in 2000, in correspondence of the sector where the sinkhole formed.

discontinuities, the deformations of the calcarenitic rock are visible with outward protrusion of wedges. Both types of fractures can isolate slices of rock of variable thickness which at later stages can cause collapse.

The rock pillars are also characterized by joint systems with different inclinations and aperture ratio. Some of these were pre-existent to the formation of the quarry, while others appear to have been caused by the high level of stress of the calcarenitic rock pushing the pillars.

These fractures can isolate blocks of metric size, causing failures from the corner of the pillars. In some cases, the fractures can run along the entire length of the pillars, causing a reduction in thickness and, eventually collapse (Figure 6).

Finite element analysis

A detailed geotechnical characterization of the Pleistocene calcarenite of Marsala is described in Arces *et al.* (2000). The rock is a medium-fine grained material, which can



Figure 6. Sub-vertical joint crossing a quarry pillar.

be classified as very to extremely soft rock, according to the recommendations provided by the International Society for Rock Mechanics (ISRM). In particular, Arces and co-workers highlight the significant influence of the saturation ratio on the uniaxial compression strength of the calcarenite samples, with strength values under saturated conditions ($\sigma_c = 1.3 - 1.6$ MPa) about half of the corresponding values for saturation degree equal to zero ($\sigma_c = 2 - 3$ MPa). A similar reduction in the values was also observed for the modulus of elasticity, measured at 50% of the uniaxial strength (E'₅₀), with values ranging between 0.03×10^4 and 0.08×10^4 MPa.

In the following model, the value of the tensile strength has been assumed to be 1/10 of the compressive strength, that is equal to $\sigma_t = 130 - 160$ kPa for saturated rock and $\sigma_t = 200 - 300$ kPa for dry conditions. Under saturated conditions, the shear strength parameters according to the Mohr-Coulomb failure criterion result to be c' = 110 - 150 kPa and $\varphi' = 35^\circ$. Further, values of c' = 165 - 220 kPa and $\varphi' = 35^\circ$ have also been considered in order to simulate conditions of low saturation degree of the calcarenite rock mass.

These parameters have been obtained as a linear approximation of the shear strength envelopes according to the Hoek-Brown failure criterion, accounting for a stress level representative of the in-situ conditions and a GSI value (Geological Strength Index; Hoek, 1994) equal to 95.

The specific parameters adopted in the model are listed in Table 1.

Table	1.	Parameters	adapted	in the	FEM	analy	/sis.
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	Dry Calcarenite GSI = 95	Saturated Calcarenite (S = 1) GSI = 95	Saturated Calcar- enite (S = 1) GSI = 80
$g (kN/m^3)$	15	15	15
E' ₅₀ (MPa)	600	300	300
n'	0.3	0.3	0.3
c' (kPa)	165	110	75
j' (°)	35	35	35
$\sigma_t(kPa)$	200	130	130
σ_{c} (kPa)	2000	1300	1300



Figure 7. A: Detailed topographic survey of the June 2011 sinkhole. Dashed lines indicate traces of the cross sections shown in figure 7B; crosses mark the topographic measurement stations. B: Cross sections of the sinkhole and the corresponding underground quarry sectors. Dashed line indicates the topography before the occurrence of the sinkhole.

Aimed at the reconstruction of the conditions that formed the sinkhole in the eastern sector of Marsala, a back-analysis with the finite element method (FEM) has been performed. Indeed, this method allows to simulate the elasto-plastic stress-strain evolution of continuous rock masses affected by the presence of underground cavities (Parise & Lollino, 2011). A two-dimensional analysis has been implemented with the numerical code PLAXIS^{2D} (Plaxis-BV 2010) by considering the cross section 6 shown in Figure 7. The constitutive model chosen for the rock mass is elastic-perfectly plastic with Mohr-Coulomb failure criterion, non associated flow (ψ = 0°) and tension cut-off.

The analyses have been carried out in drained conditions and assuming the whole domain above the water table,



Figure 8. Analysis 1 (calcarenite with low degree of saturation; GSI = 95): plastic points in the pillars of the underground quarry (above), and shear deformations in the underground quarry (below). Vertical scale is meters above sea level.

based on in-situ measurements. A numerical analysis implementing mechanical properties representative of low saturation degree conditions has been firstly carried out (Analysis 1); thereafter, an analysis implementing parameters representative of saturated conditions for the calcarenite, in the hypothesis of a rock mass characterized by low fractured conditions (GSI = 95; Analysis 2) has been performed. Such analysis is representative of conditions of calcarenite saturation at depth as an effect of long-term water infiltration from the ground surface, as typically observed during in situ surveys. Moreover, an analysis assuming saturated conditions of the calcarenite and strength parameters representative of a moderate degree of fracturing (GSI = 80) has been also performed.

The latter hypothesis follows field surveys, when at least a discontinuity set, NW-SE directed, has been identified. Thus, for this analysis a shear strength envelope, with c' = 75 kPa and $\varphi' = 35^{\circ}$ (Table 1; Analysis 3), has been used accordingly.



Figure 9. Analysis 2 (S = 1; GSI = 95): plastic points in the pillars of the underground quarry. Vertical scale is meters above sea level.

A value of the coefficient of at rest earth pressure equal to $K_0 = 1$ has been assigned to prescribe the initial stress state of the model.

Afterwards, the excavation stages have been simulated in the model up to the current geometry of the cavity rooms.

When stable conditions resulted from the model, a " $c-\varphi$ *reduction*" analysis (Matsui & San, 1992), reproducing a gradual reduction of the strength properties of the rock mass up to the global failure, has been performed in order to derive the safety factor.

For analysis 1 (dry calcarenite; GSI = 95), the numerical results show stable conditions for the rock mass. However, the analysis also indicates clear plastic zones and the accumulation of shear strains (Figure 8) within the pillars delimiting the excavation rooms. Based on the strength reduction procedure, a safety factor of F = 1.7 has been deduced in this case.

Analysis 2 (saturation degree S = 1; GSI = 95) shows a well-advanced plastic state inside the pillars dividing the rooms, with inclined plastic zones that propagate from the upper and lower pillar corners between adjacent rooms (Figure 9). For this analysis, the "c- φ reduction" calculation stage indicates a safety factor of F = 1.3 and the associated failure mechanism is shown in terms of contours of incremental shear strains and in terms of final deformed mesh (Figure 10). The upper part of Figure 10 suggests a failure process characterized by an inclined shear zone on the left-hand side of the quarry and an arch-shaped shear zone along the right-hand side. The lower part of Figure 10 shows the final profile of the

ground surface as a consequence of the failure process associated to the sinkhole. Therefore, the results define a failure mechanism which is in good agreement with the reconstruction of the collapse process, based on the field surveys (see Figure 7).

Finally, analysis 3 (saturation degree S = 1; GSI = 80) implies a lack of convergence of the numerical model and consequently unstable conditions of the rock mass (F \leq 1; Figure 11). This highlights the role of rock fracturing to enhance the failure process that led to the occurrence of sinkhole.

A comparison with similar situations in southern Italy

The situation described in the present paper for the underground quarry at Marsala is certainly not limited to this territory, or to Sicily. Presence of ancient



Figure 10. Analysis 2 (S = 1; GSI = 95): shear strains in the region overlying the underground quarry (above), and final profile of the ground surface as a consequence of the collapse (below). Vertical scale is meters above sea level.



Figure 11. Analysis 3 (S = 1; GSI = 80): plastic points in the pillars of the underground quarry. Vertical scale is meters above sea level.

underground sites used for the extraction of building and ornamental materials is extremely common in Italy, especially in the southern regions, and in those areas (i.e. Tuscany, Latium, Campania) where local geology is characterized by volcanic rocks.

It is worth here to recall the many experiences carried out during the last decades in Apulia, probably one of the regions with the highest number, and typological variety as well, of man-made cavities in Italy.

Among many types of cavities, underground quarries have produced many subsidences and sinkholes (Parise, 2010, 2012).

This because these sites, that were originally located at the outskirts of towns, have been progressively included within the built-up areas, due to progressive expansion of the urbanization, so that in many cases the constructions realized in the last decades have been built above the quarries. The cases of Altamura, Gallipoli, Cutrofiano, Canosa di Puglia are the most documented (Parise, 2012; Pepe et al., this volume). A very high percentage of the historical parts of Apulian towns are built above a complex subterranean network of quarries. Looking at the chronology of sinkhole events so far reconstructed for Apulia (Parise & Fiore, 2011), in the last decade, at least 13 sinkhole events (34 % of the total number of sinkholes with a temporal reference) can be attributed to underground quarries. There is therefore a very critical situation in terms of civil protection, as in Sicily; in this latter region, however, the problems are still greater, due to the fact that the rocks potentially interested by

such subterranean activity are represented by both volcanic rocks and recent calcarenite deposits (as in the Marsala case study).

Vulnerability of the sites is greatly increased by loss of precise locations of underground quarries, and by unavailability of a survey depicting the real directions of development of the subterranean passages, their sizes, and the interaction with the overlying built-up areas. These issues should be addressed in order to understand the instability conditions underground, and to reduce the risk of sinkhole collapses in the future.

Conclusions

In situ surveys, and numerical analyses carried out with the finite element method (FEM), allowed the authors to hypothesize the formation conditions of anthropogenic sinkholes in Marsala (Italy).

Preliminary results indicate that the genesis of the sinkhole can be attributed to the saturation of the calcarenite, along with the presence of discontinuity systems. These conditions can decrease the strength needed for the stability of the rock mass above the underground quarry.

In the case study the use of 2D modeling creates resolution limits. To obtain a more realistic representation of the tenso-deformative behavior of the rock mass a 3D model is strongly needed. 3D modeling will be part of future investigations from our working group.

In addition, it is important to notice that even if the effective quarry area is 2000 m², only 1500 m² are actually carved, giving a "rock/void" ratio of 1 to 3 or 1 to 4 if we consider the non-excavated portions (i.e. pillars, walls) over the entire area. As a consequence, after the formation of the quarry, the weight of the rock portion above a chamber is distributed over a surface reduced of ¹/₄ of the initial area. The stress on the pillars, which are often not thick enough, increases 4 times.

The case study here presented is one example of many situations that exist in Sicily, as well as in several other regions of Italy, due to the presence of underground quarries.

Caving exploration and surveys, structural analyses (including evaluation of instability features), topographic monitoring at the surface, and geotechnical modeling, represent some of the standard procedures used to evaluate the real possibility of propagation of the underground failures toward the surface.

Further, it allows researchers to obtain precious information to design rehabilitation works, or to help decision makers in the choice of the most proper action for the involved sites.

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DEVELOPMENT OF SINKHOLES IN A THICKLY COVERED KARST TERRANE

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Abstract

A cluster of aquifer drawdown-induced sinkholes developed in eastern Hillsborough County, Florida (west-central Florida), during two major freeze events in 2010. The sinkholes resulted in millions of dollars in losses and caused us to revise our thinking about how sinkholes form in a terrain normally considered to have low sinkhole risk owing to thick, clay-rich cover.

The cover material consists of the Miocene Hawthorn Group, which includes up to 120 m of interfingering expansive clay, sand and sandy clay, and carbonate strata. The lower Hawthorn Group Arcadia Formation is primarily carbonate and is up to 90 m thick. The upper Hawthorn Group Peace River Formation contains more clay and sand with minor amounts of carbonate and is up to 30 m thick. The Hawthorn Group constitutes an effective aquitard for the underlying upper Floridan aquifer (UFA), which is composed of karstic, Oligocene and Eocene limestone and dolostone.

A rapid drawdown of up to 20 m in the potentiometric surface of the underlying UFA resulted in mobilization of water-saturated clays and clayey sands within the Hawthorn Group. Subsidence and possible clay consolidation resulting from dewatering and loss of support/buoyancy caused development of new sinkholes and reactivation of clay-filled sinkholes that had developed as early as the Miocene Epoch. Stable, clay-filled, relict sinkholes of apparent Miocene age discovered in an earlier investigation in the same area in 1998-1999 support the presence of clay-filled, relict sinkholes in the area. Combining information gathered from study of these modern and relict sinkholes presents evidence of sinkhole development mechanisms in the thickly covered karst of west-central Florida.

Introduction

This paper synthesizes evidence from three karst investigations suggesting that migration or consolidation of water-saturated, expansive clay under severe, shortduration hydraulic head stresses can result in rapid sinkhole development.

The three investigations relate to sinkhole activity in different stages of development, but with apparently similar origins. From these three investigations, a case can be made for (1) rapid dewatering and consolidation or (2) movement of near-liquid, clay-rich sediments under hydraulic stress into voids in the adjacent limestone to form sinkholes.

The Three Investigations

The three investigations are discussed below in chronological order of occurrence.

Tampa Bay Regional Reservoir Investigation

In 1999, we completed site characterization for construction of an above-grade, 445 ha reservoir in southeastern Hillsborough County, Florida (Figure 1; Upchurch et al. 1999; Dobecki and Upchurch 2010). The site is located on the Polk Upland Physiographic Province (White 1970) and is underlain by a thick (up to 120 m) sequence of clay, sand, and limestone and dolostone of the Peace River and Arcadia Formations of the Miocene Hawthorn Group (Scott 1988; Arthur et al. 2008). The Miocene strata form an effective aquitard for the underlying limestone of the upper Floridan aquifer (UFA).

Three deep (>30 m) sinkhole-related features were discovered as part of the reservoir investigation (Figure 2). The reservoir embankment footprint was altered to avoid one feature that was of concern because of loose sediments in the subsurface; the second feature was a sand-filled, relict sinkhole that, based on the fill material, was determined to be contemporary with Plio-Pleistocene marine sedimentation; and the third feature (arrow, Figure 2) was filled with the green, sandy clay typical of the Miocene of Florida. This third, relict sinkhole apparently formed and was filled at the time of development of the Miocene/Pliocene unconformity.



Figure 1. The Tampa Bay area of west-central Florida. Locations of the three investigations are shown in red, and known sinkholes that have formed since 1984 are shown in violet.

The latter two features were geotechnically stable and have been subjected to 10 years of reservoir management and seasonal cycling of hydraulic heads. Groundwater levels at the reservoir are regularly monitored and it is clear that these relict sinkholes are isolated and stable. The latter two features are deemed to be safe for impounding water within the reservoir because they do not react to sudden stresses caused by drawdown in the underlying Floridan aquifer or to changes in reservoir stage.

This is not the case for the two case studies that are described below.

The Plant City Sinkhole Cluster Investigation

In January 2010 a hard freeze with overnight temperatures below 0°C that lasted eleven days near Plant City (Figure 1) in eastern Hillsborough County resulted in heavy groundwater withdrawals from the confined UFA for irrigation to protect crops from freezing. The potentiometric surface of the UFA declined up to 18 m, with up to 9 m daily excursions in potentials. As a result, at least 132 sinkholes developed within the overlying Hawthorn Group sediments within seven days of the event (Figures 3, 4).

Testing of many of these sinkholes by the authors revealed a persistent pattern: there was a thick (up to



Figure 2. North-south cross section through the reservoir to illustrate the locations and stratigraphic context of the Polk Upland sinkholes. Source: Dobecki and Upchurch 2010.

30 m) layer of expansive, smectitic clay with natural moisture contents that were at or near the liquid limits of the clays. Under standard penetration (SPT) testing, these clays had weight-of-rod or -hammer strengths (Table 1). Owing to the high clay content of the near-surface sediments, there was little evidence of suffosion; rather, many of the subsidence features reflected vertical collapse of intact, cylinder-like volumes of sediment resulting in sinkhole depths of up to 5 m and diameters of up to 50 m (Figures 3, 4).

The Southeast Hillsborough Landfill Investigation

In December 2010 there was a second, but less severe, episode of rapid drawdown of the UFA as a result of pumping for freeze protection. Shortly after this event a 45 m wide and nearly 60 m deep sinkhole (Figure 5) developed on the edge of a major Class I landfill about 3 km south of the reservoir site.

The landfill sinkhole developed in a section of mixed sand, clay and limestone strata (Figure 6). The unique feature of this sinkhole is that there is no evidence of a significant breakdown or collapse debris mound at the bottom of the aven.

It appears that the sinkhole developed over pre-existing void space where the materials had been removed from the stratigraphic column to form the aven and a bell-shaped void at the base of the aven (Figure 6). The sediments in this larger void space had also been previously removed. While the waste mass or the shallow limestone bed (Figure 6) may have bridged the void, a mechanism was required for the removal of the missing siliciclastic sediment. Refusal strength (N > 50 blows/foot of SPT penetration) sand and sandy clay

Table 1. Sample results from a standard penetration

 test boring adjacent to a sinkhole in Plant City.

Lithology	N Values*
0-8 m – Sand and sand with silt	16-49
8-32 m – Clay with minor clayey sand; expansive (LL = 104%, PI = 42%); 2 clayey sand seams were approx. 1.5 m thick	0-29 (weight-of- rod- or ham- mer- strength clay for 5.5 m)
29-36 m (end of boring) - Limestone with chert	72-100+

*Blows/ft. penetration



Figure 3. A large sinkhole that developed by vertical movement near Frostproof, Florida. Note the intact trees in the down-thrown sediment "plug."



Figure 4. Sinkhole that developed in a suburb of Plant City. This was one of seven on the street. Sand has been placed in the foreground to reduce risk of additional damage to the street.



Figure 5. The landfill sinkhole in southeastern Hillsborough County, Florida. Note the slump features developed within the waste mass.



Figure 6. North-south cross section of the landfill sinkhole. (Note that depths are presented in feet and that the cross section was developed from standard penetration testing after initial stabilization of the sinkhole and backfilling to allow safe access for testing. CLSM is cementitious Controlled Low Strength Material used to cap the aven and stabilize the site) Source: on-going investigation by the authors.

surrounds most of the void. As such, the walls of the aven and bottom void are well supported. However, the perplexing question is: where did the collapse material go?

It appears that the sediments that occupied the void space had been washed out of the space at some earlier time, perhaps during the freeze event in January 2010 or even earlier. This would explain the absence of breakdown debris at the bottom of the void. The void, therefore, was either bridged over by the upper limestone, which was not detected as rubble at the base of the void, or perhaps the waste mass itself.

Interpretation, Conclusions, and Epilogue

Based on comparisons of the results from the three investigation areas, we suggest that the Polk Upland sinkholes developed as follows (Figure 7):

1. The Polk Uplands are underlain by the Miocene Hawthorn Group. The Hawthorn Group includes

clay, sand, and carbonate units (Figures 2 and 6). These strata form an effective aquitard that confines the underlying UFA. When extremely heavy withdrawals of groundwater from the UFA occur, lack of concomitant leakage from overlying water sources (surficial aquifer, surficial water bodies, localized aquifers within the confining unit) causes sharp, short-term declines in the potentiometric surface.

- 2. Karst features, including sinkholes, began to develop in the Hawthorn Group near the end of Miocene time (the post-Hawthorn unconformity; Scott 1988). Some sinkholes were filled with Miocene clay and others with younger Plio-Pliocene marine sands. The features thought to have formed this way at the reservoir contain strong, well-consolidated sediments that appear unaffected by modern hydraulic stresses.
- 3. Elsewhere, some of these features appear to have been filled with clay and clayey sand that has not been well consolidated, resulting in localized



Figure 7. Potential mode of sinkhole formation within the clay-rich strata of the Hawthorn Group on the Polk Uplands of Florida.

pockets of soft clay with natural moisture contents near or exceeding their liquid limits.

4. When sudden and short-term, deep declines caused by groundwater withdrawals occur in the potentiometric surface of the UFA, some of these under-consolidated clay and clayey sand deposits may fail, either by simple dewatering and rapid consolidation or by migration of the clay and associated sandy sediments into the voids of the subjacent limestone (Figure 7).

As shown in Figure 7, our current concept as to how these sinkholes form is by migration of clay and clayey sand into void space in adjacent Hawthorn Group limestone or the underlying Oligocene and Eocene limestone of the UFA. The fluid nature of the saturated, expansive clays and clayey sands allow them to migrate farther laterally than might be otherwise expected into void space not directly beneath the sinkhole. This migration explains why there was no evidence of breakdown or collapse materials, other than landfill waste, on the floor of the Southeast Hillsborough Landfill sinkhole.

Clay and clayey sand remain under the sinkholes we tested near Plant City. In this case, either the clay and clayey sand were simply dewatered and consolidated or migration into nearby void space was incomplete. While this clay and clayey sand sediment is poorly consolidated, water-saturated, and near its liquid limit, sudden migration of water out of the clay mass would be hindered by the low intrinsic permeability of the material. Therefore, partial physical migration of the near-liquid clay seems the better hypothesis, a process that links these sinkholes genetically with the Southeast Hillsborough Landfill sinkhole.

The Polk Uplands remain a low sinkhole probability area, but when sinkholes develop they can be locally common, large, and catastrophic. The ones we investigated appear to have been triggered by significant, short-term hydraulic gradients caused by groundwater withdrawals from the highly confined UFA.

The local water-use permitting agency, the Southwest Florida Water Management District, has taken steps to minimize future major drawdown events by declaring a water caution area and adopting additional regulations related to water use and sources.

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PALEOKARST CRUST OF ORDOVICIAN LIMESTONE AND ITS CAPABILITY IN RESISTING WATER INRUSHES IN COAL MINES OF NORTH CHINA

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Abstract

With increase in mining depth of the Carboniferous-Permian coal seams in North China, it is particularly important to study the heterogeneity of karst development in the underlying Middle Ordovician limestone and determine any impermeable strata that may prevent the pressurized karst water from bursting into coal mines. Detailed analysis of the exploratory borehole data suggests presence of a paleokarst crust at the top of Middle Ordovician Fengfeng Formation. Because of its mechanical strength and low permeability to water, the paleokarst crust can function as an additional waterresisting layer. This paper takes Sihe Mine of Shanxi Province as an example to study the geotechnical and hydrogeological characteristics of the paleokarst crust. Incorporation of this additional hydrological barrier led to more minable coal seams in the coalmine.

Introduction

Middle Ordovician limestone and Carboniferous-Permian coal seams are widespread in North China, as shown in Figure 1. Mining of the coal seams in the past few decades has led to multiple theories and techniques of evaluating the pressurized water from the limestone into underground mining areas. These theories emphasize the potentiometric pressure in the Middle Ordovician limestone and the aquifuge between the coal seams and the Middle Ordovician limestone. The term "aquifuge" is defined in this paper as an impermeable body of rock which contains no interconnected openings or interstices and therefore neither absorbs nor transmits water and it is interchangeable with the term "aquiclude." The most commonly used water inrush coefficient is defined by:

T=P/M

where T is the water inrush coefficient; P is the potentiometric pressure; and M is the thickness of aquifuge. The greater the water inrush coefficient is, the more likely occurs a water inrush. The potentiometric

pressure is typically measured at monitoring wells in the Middle Ordovician limestone while the limestone has been treated as a unified aquifer system. Determination of the aquifuge thickness is less definitive but it is an equally important parameter. Similar approaches are used in other countries (Verbovsek and Veselic 2008; Hawkins and Aljoe 1992).

With increase in mining depth of the Carboniferous-Permian coal seams, the potentiometric pressure of the Ordovician groundwater becomes higher, indicating a higher risk of water inrush. It is particularly important to study the heterogeneity of karst development in the underlying Middle Ordovician limestone and determine any impermeable strata that may prevent the pressurized karst water from bursting into coal mines. Detailed analysis of the exploratory borehole data suggests presence of a paleokarst crust (hereinafter referred to as crust) at the top of Middle Ordovician, which is often referred to as the Fengfeng Formation (Figure 2). The enormous variation in water-resisting capacity makes recognition and application of the crust less straightforward in coal mining.

Studies on Paleokarst Crust

Studies by Li and Wang(1997)indicate that the Early Carboniferous strata were re-deposited after 150 million years (Ma) of the Middle Ordovician, which resulted in the ubiquitous Bauxite mudstone. The top Middle Ordovician was further compacted and any fractures would have been filled by the overlying fragments of mudstone. Large voids were difficult to exist because of weight of the overlying strata (Li and Wang 1997; Li et al. 1997). A schematic diagram is shown in Figure 3 to illustrate this concept. Between 2009 and 2011, Bai and others (2009a; 2009b; 2010; Miu and Bai 2011) published a series of research findings about mining above the Fengfeng Formation in the Lu'an Mining Area and Xuzhou Ming Area and formed a new concept for controlling water hazards and utilizing water resources.



Figure 1. Distribution of coal resource and aquifuge in North China.

Based on thin section analysis of rock samples, X-ray fluorescence spectrometry, and rock microstructure analysis, Wang and Bai (2009) analyzed the lithology, karst pore structure and distribution in the Fengfeng Formation in Zhangcun Mine of Lu'an Ming Group, Shanxi Province. Their results show approximately 140 meters (m) aquifuge in total at the top and bottom of the Fengfeng Formation. Bai and others (2009) proved the presence of the aquifuge by statistic analysis of data collected in Shandong, Shanxi, and Hebei Provinces.

The presence of aquifuge may explain why the water inrush did not occur in the theoretically predicted water bursting areas, while it occurred in the anticlinal development areas (Wang and Bai 2009). Fu and others (2010) took samples from the Fengfeng Formation in Wang Jialing Mine in Shanxi Province and divided the Fengfeng Formation into four zones:

- Weathered and leached zone
- Upper section with gypsum
- Thick micrite section
- · Lower section with gypsum

Of the four zones, the lower section appears to have a strong water-resisting capacity.

Characteristics of Paleokarst Crust at Sihe Mine

Sihe Mine is in Shanxi Province (Figure 1), which is a large anthracite base with an annual production of 1,200 million tons. The average thickness of the Fengfeng Formation is approximately 100 m. The distance between the lower coal seams and the Middle Ordovician limestone is approximately 20 m. The water pressure exerting on the coal seam floor ranges from 1 to 3 megapascal (MPa). The potential of



Figure 2. Typical geological column in North China coal fields.

water inrush has become a key factor restricting its sustainable production at the mine.

Lithology of Fengfeng Formation

Figure 2 shows the relationship between the coal seams and the underlying limestone formations. The Fengfeng Formation at Sihe Mine consists of cyclic deposition of pure limestone and argillaceous limestone with variable thicknesses. It does not constitute a water-resistance layer in its unaltered state. This cyclic depositional structure is common in the middle of the Fengfeng Formation with a thickness between 20 and 50 m. The top 20 m of the Fengfeng Formation is pure limestone which is the country rock for the paleokarst with any fractures filled with calcite and weathering residuum. This altered top section of the Fengfeng Formation provides a geologic barrier to groundwater flow.

Fractures in Fengfeng Formation

Three types of fractures were observed in the Fengfeng Formation: cross joints, inter-laminar joints, and microstructural fractured fractures (Figure 4). The upper part of the Fengfeng Formation mainly develops the microstructural fractures with the joints being secondary. The lower part of the Fengfeng Formation is a water-bearing region and the paleo-karstification and weathering is not as obvious as the top part. The main form of fractures is either oblique cross joints or inter-laminar joints.

Filling materials

Physical and chemical weathering over 150 Ma has produced a large amount of breccia cemented with calcite, the weathering residues, or argillaceous filler. As shown in Figure 5, the high extent of cementation and filling in breccia or fractures makes the paleokarst crust in the Fengfeng Formation possess strength and water-

	Coal Seams	and the last solution of the solution of the
0. 0. 0. 0. 0. 0.	Bauvitic-mudstone Sandy-mudstone mudstone	0. 0. 0. 0. 0. 0. 0. 0.
0. 0. 10. 0. 0. 0. 0.	Dallatite mutatonevoandy mutatonev mutatone	0.10.0.0.0.0.0
· · · · · · · · · · · · · · · · · · ·		0-0-0-0-0-0-0-0
	Solution cavity with Shanxi type of iron deposit	p= 1 Q- 0- 0- 0- 0- 0-0
a) 000 0 000000000000000000000000000000	and other weathering residues	P
AL A A A A A A A A A A A A A A A A A A	1000 A 1 1 4 1 4 1 4 1 4 1 4 1 4 1 4 1 4 1 4	SALLALA ALA
	a a a a a a a a a a a a	
A A A A A A A A A	a la la la la la	A Weathered limestone
	karst-fissure	
bedrock		

Figure 3. Palaeokarst profile in Fengfeng Formation.



a. Oblique cross joint b. Inter-laminar joint Figure 4. Three different types of fractures in Fengfeng Formation.

micro-structural fractures



Figure 5. Cemented fractures in Fengfeng Formation.

resisting capacity. The characteristics of geologic barriers in preventing water inrushes are discussed in Zhou and Li (2001).

Water-resisting capacity

Pumping tests, flow-rate logging, chemical analyses of groundwater, and water-pressure tests were conducted to determine the water-resisting capacity and spatial distribution of the aquifuge in the Fengfeng Formation. The hydrogeological characteristics of the Fengfeng Formation were then compared with those of the underlying upper Majiagou Formation (Figure 2), which is often considered as a strong aquifer.

Results of water-pressure tests

The water-pressure tests were conducted in thirteen boreholes. The technique of conducting the pressure tests is detailed in Zhou and Li (2001). The test results show that the top 35 m of the Fengfeng Formation has an extremely poor permeability ranging from 0.00002 to 0.00024 m/d, which indicates that this part of the stratum has a certain water-resisting capacity. The water pressure in the Ordovician limestone gradually decreases in the underlying stratum. The thickness of this part is 8.6 m and the water pressure drop is 3.27 MPa. As a result, the water resistance coefficient is approximately 0.38MPa/m.

Hydrogeogical Properties of Fengfeng Formation Drilling fluid loss

Of seventeen Ordovician hydrogeological boreholes drilled in the Fengfeng Formation in Sihe Mine, fourteen boreholes lost drilling fluid at normal rates from 0.1 to 1 m3/h and only three encountered significant loss of more than 1 m3/h in the lower segment of the Fengfeng Formation. Of the sixteen boreholes drilled through the upper Majiagou Formation, eight boreholes' consumption of drilling fluid was at normal rates and significant or massive loss occurred in the other eight boreholes in the middle segment of the upper Majiagou Formation. The difference of drilling fluid loss between the Fengfeng Formation and upper Majiagou Formation suggests that the fractures in the Fengfeng Formation might have been filled and the formation is not as conducive to water flow and storage.

Pumping test results

Table 1 lists the thirteen boreholes in which pumping tests were conducted in both the Fengfeng Formation and the upper Majiagou limestone. The specific capacity of the Fengfeng Formation is between 0.0009 and 0.0058 l/s.m. Those values are two to three orders of magnitude smaller than those of the upper Majiagou Formation combined, which ranges from 0.0005 to 0.594 l/s.m. In addition, the water level of the Fengfeng Formation is apart from that of the upper Majiagou Formation, with a difference ranging from 1.1 to 37.6 m. The tests have proved that the water abundance of the Fengfeng Formation is much weaker than that of the upper Majiagou Formation.

Hydrogeochemical test results

Figure 6 shows the Piper diagrams based on the water samples collected in these thirteen boreholes at which the pumping tests were conducted. The main anion in the Fengfeng Formation is SO42-, secondly CL-, while the content of HCO3- is little. The main cations

	Comparison of water level		Comparison of Specific Capacity			
					Majiagou and	Ratio of
Borehole	Fengfeng	Majiagou	Difference	Fengfeng	Fengfeng	Combined and
	Formation	Formation	Difference	Formation	Formations	Fengfeng
					Combined	Formation
SWY2	555.8	521.2	34.6	0.000942	0.000859	0.9
SC2	449.7	483.5	33.8	0.001	0.188	188
GZ	450.9	481.5	30.6	0.00588	0.0366	6.2
SWY1	482.4	493	10.6	0.0026	0.144	55.4
SB1001	511.4	488.79	22.61	0.000477	0.13947	292.4
SB1002	546.54	508.94	37.6	0.00299	0.112379	37.6
SB1003	544.92	513.54	31.38	0.004489	0.06624	14.8
SB1004	495.46	478.75	16.71	0.004721	0.044552	9.4
SB1005	466.84	477.75	10.91	0.0004	0.00052	1.3
SW2	497.7	513.1	15.4	0.00305	0.00324	1.1
SWY3	488.7	487.6	1.1	0.00478	0.594	124.3
SC3	489.2	487.1	2.1	0.00435	0.0268	6.2
SW1	512	488.4	23.6	0.00403	0.302	74.9

Table 1. Result of Ordovician limestone pumping tests

in the Fengfeng Formation are Ca2+ and Mg2+. The composition of mixed samples of the Fengfeng and Maijiagou Formations is quite different. The main cation is Ca2+, and the main anion is SO42-, followed by HCO3-. These observations indicate that the Fengfeng Formation is in a more reductive environment than the Majiagou Formation. The water in the Fengfeng Formation has poor circulation, which is evidenced by the lack of HCO3-, a common cation in good groundwater flow conditions.

Flow rate logging results

Based on the flow rate logging results in six boreholes, no flow date could be obtained in the Fengfeng Formation because of its poor water yield. In comparison, obvious flow rate data were obtained in the Majiagou Formation. In addition, more boreholes showed greater water flow rates in the middle of the Majiagou Formation than in the top zone.

Thickness of aquifuge in Fengfeng Formation

In North China, the water abundance of an aquifer is often divided into four classes based on specific capacity:

- >5.0 l/s.m very strong
- 1.0 5 l/s.m strong
- 0.1 1.0 l/s.m moderate
- =0.1 l/s.m —weak



Figure 6. Piper diagrams for groundwater in Fengfeng Formation (a) and Majiagou Formation (b).

The specific capacity of the Fengfeng Formation is between 0.0009 and 0.0059 l/s.m, which falls in the category of a weak aquifer or relative water-resisting aquifuge. The thickness of relative aquifuge ranges from 35 and 70 m based on the summary statistics.

Conclusions

Significance of the water-resisting ability of Ordovician limestone for mining above an aquifer

- 1. Problems of mining above an aquifer are increasingly serious in North China. In Sihe Mine for example, after considering the relative aquifuge, more than 90 million tons of coal resources are considered to be not threatened by the underlying pressurized water. Careful analysis of the potential water-resisting capacity of the Fengfeng Formation helps understand the real conditions when mining above the aquifer. The Ordovician limestone may not be a unified karst aquifer system but consist of protective barriers. Recognition of the heterogeneous nature provides us with a new approach for evaluating water inrushes when mining above an aquifer.
- 2. Based on studies on the water-resisting capacity of the paleokarst crust in top part of the Middle Ordovician limestone, the paleokarst crust can be treated as an aquifuge with a thickness of 35-70 m in Sihe Mine.
- 3. When doing a study on the hydrogeological features of the Ordovician limestone, a multidisciplinary approach, such as water abundance, hydrochemistry characteristics, permeability of strata, and strata combination, is needed to make the most appropriate judgment.
- 4. The water-resisting capacity of the paleokarst crust in the coal fields of North China may be variable in different areas. In some areas it may not exist. However, recognition of the potential significance of the paleokarst crust may increase the coal production or lengthen the operation of a mine.

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DEEP TIME ORIGINS OF SINKHOLE COLLAPSE FAILURES IN SEWAGE LAGOONS IN SOUTHEAST MINNESOTA

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Abstract

Three of the approximately twenty-three municipal wastewater treatment lagoons constructed in the 1970s and 1980s in southeastern Minnesota's karst region have failed through sinkhole collapse. Those collapses occurred between 1974 and 1992. All three failures occurred at almost exactly the same stratigraphic position. That stratigraphic interval, just above the unconformable contact between the Shakopee and Oneota Formations of the Ordovician Prairie du Chien Group is now recognized as one of the most ubiquitous, regional-scale, karst hydraulic high-transmissivity zones in the Paleozoic hydrostratigraphy of southeastern Minnesota.

These karst aquifers have been developing multi-porosity conduit flow systems since the initial deposition of the carbonates about 480 million years ago. The existence of syndepositional interstratal karst unconformities between the Oneota and Shakopee Formations and between the Shakopee and St. Peter Formations, were recognized in the 1800s. About 270 million years ago galena, sphalerite and iron sulfides were deposited in pre-existing solution enlarged joints, bedding planes and caves. The region has been above sea level since the Cretaceous and huge volumes of fresh water have flowed through these rocks. The regional flow systems have changed from east-towest in the Cenozoic, to north-to-south in or before the Pleistocene. The incision of the Mississippi River and its tributaries has and is profoundly rearranging the ground water flow systems as it varies the regional base levels during glacial cycles. The Pleistocene glacial cycles have removed many of the surficial karst features and buried even more of them under glacial sediments. High erosion rates from row crop agriculture between the

1850s and 1930s filled many of the conduit systems with soil. Over eighty years of soil conservation efforts have significantly reduced the flux of mobilized soil into the conduits. Those conduits are currently flushing much of those stored soils out of their spring outlets. Finally, the increased frequency and intensity of major storm events is reactivating conduit segments that have been clogged and inactive for millions of years.

The karst solution voids into which the lagoons collapsed have formed over 480 million years. The recognition and mapping of this major karst zone will allow much more accurate karst hazard maps to be constructed and used in sustainable resource management decisions.

Introduction

Three of the approximately twenty-three municipal wastewater treatment facility (WWTF) lagoons constructed in the 1970s and 1980s in southeastern Minnesota's karst region have catastrophically failed through sinkhole collapse (Alexander and Book, 1984; Jannik et al., 1992; Alexander et al., 1993). These lagoons are non-mechanical systems that rely on sunlight, air and microbes to treat the wastewater. The first lagoon to fail, the Altura WWTF lagoon, collapsed twice. All four collapses occurred in the same stratigraphic position. That stratigraphic interval is centered on the unconformable contact between the Shakopee and Oneota Formations of the Ordovician Prairie du Chien Group (Mossler, 2008). That interval is a regional-scale, karst hydraulic hightransmissivity zone in the Paleozoic hydrostratigraphy of southeastern Minnesota (Runkel et al., 2003; Tipping et al., 2006). The interval has long been known as a productive zone by the water well drilling community.

The sinkhole collapses were induced by the lagoons' construction and operation. Were these collapses random, unpredictable "acts of God"? Or did the collapses result from the interactions between deep time geology with recent human activities? Can we improve the safety of future analogous facilities? Can we evaluate/prioritize the future collapse risk of the regions' remaining WWTF lagoons? These questions are the focus of this paper.

Hydrogeologic Setting

Mossler (2008) and references listed therein are the basis for much of this section. To construct the current lithostratigraphic nomenclature of Minnesota's Lower and Middle Paleozoic sedimentary rocks, Mossler definitively reviewed the region's structural and sedimentological framework.

Most of Minnesota's karst features and important bedrock karst aquifers occur in southeastern (SE) Minnesota the area roughly south and east of the Twin Cities Metropolitan area. SE Minnesota forms the east limb of the gently southward dipping Hollandale Embayment. The regional dip is about two meters per kilometer to the southwest but local structures with several meters of amplitude are hydrogeologically important.

Figure 1 shows the structural context of the Middle and Lower Paleozoic rocks in the upper Mississippi River Valley (UMV). The adjacent areas in southwestern Wisconsin, northwestern Illinois and northeastern Iowa, with southeastern Minnesota, comprise the UMV Karst.

The Paleozoic sedimentary units are relatively thin, regionally extensive, siliciclastic and carbonate rocks that can be correlated across the UMV Karst. These rocks were deposited during three episodes of complex sea transgressions during the Paleozoic. The tops of each episode are characterized by interregional unconformities. Because SE Minnesota was near the center of the craton, it was among the last places to be flooded during transgression and the first to be exposed to erosion as the sea withdrew. The tops and bottoms of many of the units are marked by erosional unconformities.

Conventional geologic columns show the sequence of rocks exposed as the rocks appear in outcrop or drill core. The columns diagram the rock types and linear thicknesses. The geologic ages of the rocks are indicated in a non-linear fashion. Erosional unconformities can



Figure 1. Regional geologic setting of the Lower and Middle Paleozoic rocks in SE Minnesota (Mossler, 2008, Figure 2B).

be seen but are inconspicuous. Figure 2 is a simplified geologic column from SE Minnesota modified from Mossler (1987, 2008). This column nicely demonstrates that siliciclastic sandstones, mudstones and shales dominate in the upper Cambrian column of SE Minnesota, that carbonates dominate in the Ordovician section and that the two fundamentally different rock types are inter-fingered.

A conventional geologic column is one of the most basic conceptual tools used by hydrogeologists and geoengineers to understand and describe the region. Geologic columns are a fundamental tool to present geologic concepts to the public. From a karst perspective, however, they have an important failing. They significantly underemphasize the number, magnitude and importance of unconformities formed by erosion. It was during these erosion periods that karst features could and did develop. The unconformities have been emphasized with bold black lines in Figure 2.

Figure 3 is Mossler's (2008) SE Minnesota Geologic column displaying the same information on a linear time scale. This geologic column emphasizes the relatively rapid deposition of the lower siliciclastic-dominated rocks. The Upper Cambrian Mt. Simon through the Jordan, i.e. roughly 250 m (820 ft) of siliciclastic rocks, were deposited in about 10 million years. The remaining about 100 m (330 ft) of the Lower Ordovician Prairie



Figure 2. Lithostratigraphic column for the Lower and Middle Paleozoic rocks in southeast Minnesota. The bold black, wavy lines emphasize the unconformities. Modified from (Mossler 1987, 2008).







du Chien carbonates were deposited in two roughly 5 million year episodes with a 5 million year gap between.

An unconformity representing a gap of over 15 million years separates the Prairie du Chien from the Upper Ordovician St. Peter through Maquoketa sequence, which was deposited in about 10 million years. The Devonian Spillville through Lithograph City carbonates represent about 15 million years of time, including three significant unconformity gaps. The remaining 135 million years of the Cambrian through Devonian time left no depositional record in SE Minnesota. During those enormous unconformity time gaps the lower Paleozoic carbonates were infiltrated by fresh surface waters and subject to karst solution.

Karst Processes in SE Minnesota and the mid Prairie du Chien karst high-transmissivity zone

Paleozoic karst processes

Hedges and Alexander's (1985) review of karst features in the UMV region gathered references to "paleokarsts of Ordovician, Devonian, Pennsylvanian and Cretaceous ages" and "interstratal karstification between the Shakopee dolomite and the overlying St. Peter sandstone, between the Oneota dolomite and the overlying New Richmond sandstone and between the Oneota dolomite and the underlying Blue Earth siltstone." Geologic references to paleokarst features in the UMV date back at least to Barris (1880) and Farnsworth (1888). Farnsworth (1888) refers to an 1854 Iowa Geological Survey report of clay filled caves and fissures in Devonian limestones (Hall and Whitney, 1858).

Karstification of the top of the Oneota Formation during the 4 to 5 million year subaerial erosional unconformity before the deposition of the Shakopee Formation and subsequent regional groundwater flow systems, extending to the present day, have produced arguably the most significant, best developed and mappable hightransmissivity zone in the Paleozoic hydrogeology of SE Minnesota.

Runkel et al. (2003) and Tipping et al., (2006) have documented the hydrogeologic importance of this feature. Figure 4 diagrams the position and extent of this feature in southeastern Minnesota. The mid-Prairie du Chien karst high-transmissivity zone is a very old feature. It started as solution weathering and karstification of the top of the Oneota during the 4 to 5 million year unconformity between the Oneota and the overlying Shakopee. The geometry of the overlying Shakopee, itself highly karstified beneath the sub-St. Peter large magnitude unconformity, insured that the stratigraphic interval would localize what is a regional scale flow system.

Smith (1997) documented that solution removal of anhydrite and the subsequent brecciation of the eroding top of the Oneota played an important role in developing the karst high-transmissivity zone, during the subaerial weathering before the deposition of the Shakopee. Smith et al. (1997) further emphasize that authigenic silica fabrics present in this unconformity document that silicification occurred before and during the erosional unconformity, i.e., that karstification was syndepositional.

About 270 million years ago galena, sphalerite and iron sulfides were deposited in pre-existing solutionally enlarged joints, bedding planes and caves in the UMV. This includes precipitation of these mineral into macropores associated with the paleokarsts feature in the upper Oneota dolomite (Runkel et al., 1993).

Karst processes from the Mesozoic to present

The UMV region has been above sea level since the Mesozoic and huge volumes of fresh water have flowed through these rocks. The regional flow systems have changed from east-to-west in the Mesozoic and Cenozoic, to north-to-south in or before the Pleistocene. The climate was warm to tropical during much of this period and karst process must have been an important component of the ongoing surficial processes. The incision of the Mississippi River and its tributaries has and is profoundly rearranging the ground water flow systems as it changes the regional base level during glacial cycles.

The Pleistocene glacial cycles removed much of the preexisting epikarst and many surficial karst features. Large areas of karstified carbonate bedrock were buried under 50 to 150 meters of glacial sediments with the internal karst features intact. High soil erosion rates from row crop agriculture between the 1850s and 1930s filled



Figure 4. Southeast Minnesota hydrostatigraphic cross section, schematically showing solutionally-enhanced fractures and voids (not to scale). The karst high-transmissivity zone near the middle of the Lower Ordovician Prairie du Chien Group is highlighted in red.

many of the conduit systems with soil. Soil conservation efforts that began in the 1930s have significantly reduced the amount of soil moving into the conduits. Precipitation events are now flushing stored sediment out of the conduits.

The increased frequency and intensity of major storm events over the past few decades may be reactivating portions of conduit segments that have been clogged and inactive for millions of years. There may be many currently inactive conduits (plugged by ancient, glacial and modern sediments) that are being reactivated as hydrologic conditions change and the plugs are flushed out.

The contact zone between the Prairie du Chien and the Shakopee has long been known as a productive zone by the local water well drillers. This cavernous zone is easily recognized in hydrophysical logging of area water wells.

Dalgleish and Alexander (1984, Figure 7, p. 83) documented the dominance of this stratigraphic interval on the distribution of sinkholes in Winona County, where three of the four collapses occurred. In Wabasha County, which contains the fourth collapse site, sinkholes are more likely to occur where this stratigraphic interval

coincides with the water table position (Tipping et al., 2001). Finally, that the four sinkhole collapses in WWTF lagoons were constructed where this zone is the uppermost bedrock (Alexander and Book, 1984; Jannik et al., 1992; Alexander et al., 1993) further emphasizes the geoengineering and environmental management importance of this zone in SE Minnesota.

Conclusion

The collapse of the Altura, Lewiston and Bellchester, Minnesota, WWTF lagoons were not random, unpredictable events. The collapses occurred as a result of siting the lagoons immediately on top of the mid-Prairie du Chien high-transmissive zone—the largest, most developed regional karst solution zone in SE Minnesota.

The opportunity and the challenge

When these WWTF lagoons were designed and built in the 1970s and 1980s, the current understanding of the hydrogeologic and environmental importance of the mid-Prairie du Chien karst high-transmissivity zone did not exist. The basic geologic information existed but had not been assimilated into the hydrogeologic or geoengineering communities who designed and built the lagoons. That technical information had also not been transmitted to regulatory officials. No one recognized that a problem existed, much less how to prevent it.

We now have the tools and knowledge to incorporate more focused, nuanced karst hydrogeology and geoengineering concepts and practices into evaluating and managing the operation of in-place infrastructure and practices. We can upgrade the design and operation of new infrastructure and practices.

The use of karst hydrogeologic and geoengineering concepts to collect, interpret and apply new tools to gather much larger quantities of higher quality, more detailed data and information to infrastructure siting and management issues is very promising. One example is the use of modern Geographic Information System tools, accurate Global Positioning Satellite technology, LiDAR DEMs and surface feature maps, growing data bases of local subsurface information from well drillers and other sources, and a variety of geophysical tools. Such tools significantly enhance the precision and accuracy of more traditional bedrock, structural and karst mapping techniques. We have the ability to create accurate, specialized subcrop area maps of the mid- Prairie du Chien karst high-transmissive zone. Such maps will allow the existing infrastructure to be prioritized according to relative sinkhole failure probability, and to guide siting decisions for future infrastructure. These maps can also be used to influence resource management decisions.

Acknowledgments

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EMERGENCY INVESTIGATION OF EXTREMELY LARGE SINKHOLES, MAOHE, GUANGXI, CHINA

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Abstract

A series of sinkholes collapsed at Maohe village, Liuzhou, Guangxi, China. The collapsing event formed 41 sinkholes, 11 donut-shape subsidence areas and 68 fractures in May of 2012. Many ground failures and fractures formed and an area of 40000 m² was impacted by the collapsing event. The collapsing event was caused by large scale soil piping and soil void collapses. Preliminary investigations revealed that drastic fluctuations of karst water level caused this collapsing event. Heavy precipitation along with bedrock roof collapse of underground streams may trigger a "water hammer" effect in the karst conduits. The "water hammer" effect caused severe soil damage and subsequent collapses in Maohe Village. Soil disturbance may cause a change in hydraulic gradient, causing water level fluctuations that eventually resulted in sinkhole collapses. By monitoring pressure changes of karst water, turbidity of groundwater, locating soil voids and soil disturbances using ground penetrating radar (GPR), it is possible to predict future sinkhole collapses.

Introduction

On May 10 2012, a series of sinkholes collapsed at Maohe village, Liuzhou, Guangxi, China. The collapsing event formed 15 sinkholes ranging from 4 to 30 m in diameter and 2 to 10 m in depth within one hour after 10:20 am. By May 15, 41 sinkholes collapsed. Eleven donut-shape subsidence areas and 68 fractures formed in the area. Many ground failures occurred and an area of 40,000 m² was impacted by the collapsing event and an area of 10,000 m² suffered severe damage. Because the collapsing events occurred in areas with high population density, an initial investigation revealed severe damage of 143 residential houses (69 collapsed), 8 factory buildings, and 3 buildings currently under construction. Two elementary schools and one middle school were impacted and 1830 people were relocated. Direct loss of property damage is estimated to be at least 20 million CNY (> 3 million US dollars). This paper discusses the geologic background of the study, mechanism of sinkhole collapses, and prevention and treatment of sinkhole hazards in the study area.

Geologic Setting

Maohe village is located in a highly active karst area and many karst features such as sinkholes, springs, karst windows, caves, and conduit systems are widely distributed in this area. The area is a typical karst plain with isolated karst towers. The altitude of the ground surface is about 92.53 - 94.16 m. The unconsolidated sediments above bedrock are Quaternary alluvium and colluvium deposits with thicknesses ranging between 3.70 m and 17.10 m. The Quaternary deposits are comprised of colluvium clay, silty clay, rounded gravels, and red clay. The bedrock is thick light-gray dolostone belonging to the middle Carboniferous Dapu formation (C_{2d}) . The dolostone is brittle with many fractures and joints. The upper layer of bedrock dips to the east with dipping angles less than 5 degree. The altitude of the top of the bedrock is 74.30 - 87.76 m and depth to bedrock is 4.70 - 38.50 m (Figure 1).

The study area is a covered karst area. Bedrock is highly fractured due to faulting and tectonic movements. Karstification is highly active along joints and fault zones, which causes more relief of bedrock topography. Voids and caves are commonly encountered during drilling processes. Thirty three out of 71 (46.5 %) drilling cores showed that caves exist within bedrock. Sixty six caves are detected from drilling with heights ranging from 0.20 to 14.60 m. The number of caves decreases drastically with depth and almost all caves are distributed within the uppermost 20 m of bedrock. Most caves were filled with clay and dolostone debris, especially caves close to the top of the bedrock. Fifty two caves are filled and 14 caves are empty. The filling rate is 78.8% (Figure 2).



Figure 1. Geologic Map of the study area.

Groundwater resources include water in porous Quaternary deposits and karst water within bedrock matrix, fracture, and conduits. A limited amount of Quaternary water is mainly stored within a silty clay aquifer with a depth of 1 - 7 m and water level ranges between 1 and 3 m. A significant amount of karst water exists in fractures and conduits of the dolostone bedrock. The depth of the water table ranges between 1.60 and 5.95 m and the altitude of the water level is 88.25 - 90.02 m.

Water Pumping and Sinkhole Distribution

There is only one deep well that pumps in this area. The well was drilled in 1990 and is located in the northeastern corner of the study area. The well depth is 95 m and the average pumping rate is approximately 150 m³/day. There are many hand-dug wells in Shangmuzhao section used for laundry. Most domestic water usage is from city water systems. No heavy pumping of groundwater ever occurred and a cone of depression does not exist in the study area.

Forty-one sinkholes, 11 donut-shaped subsidence areas, and 68 fractures formed in the area (Figure 3 & 4). Most sinkholes are circular or elliptical in shape on the surface and cone shape below surface. The largest sinkhole is no. 11 with an irregular shape on the surface and a long axis

of 70.0 m, short axis of 12.0 - 38.0 m, and a depth of 4.0 m. The smallest sinkhole is no. 30 with a diameter of 1.2 m and a depth of 5.0 m. Groundwater flowed out to the surface when this sinkhole collapsed and all of the water disappeared through the bottom of the sinkhole after a few minutes. Subsidence area no. 2 is the largest with an irregular shape on the surface and a length of 33.0 - 36.0



Figure 2. Subsurface cave distribution based on drilling records.Vertical axis indicates elevation (m) above sea level.



Figure 3. Sinkhole distribution in the study area.



Figure 4. Typical sinkhole collapses in the study area.

m, width of 23.0 - 26.0 m, and a depth of 1.0 m at the center of the subsidence. Four fractures formed around this subsidence area, which caused building no. 4 to be tilted to the north.

Most sinkholes formed at the Shangmuzhao section of Maohe village and the overall distribution is along zones of NW – SE orientation. The water was turbid in a handdug well and many air bubbles were released from the well on May 10. Total suspend solids were about 10% from pumped groundwater. By May 14, the well had already collapsed (Figure 5).

Results and Discussion

Collapsing events were caused by soil piping and deformation due to highly fluctuating hydraulic conditions within the karst water system. Karst features such as cave streams, large karst springs, karst windows, caves, and blue holes exist in the study area.

On-site investigations revealed that initial collapses occurred during heavy rainfall. Rapid water level rise caused cave roof collapse, which may trigger a "water hammer" effect in the karst conduit system. The "water hammer" effect can release a pressure surge to the karst conduit system, causing severe soil damage and subsequent collapses (Lei et al., 2010; Gao et al., 2013). Soil disturbance would change the hydraulic gradient, which can cause water level fluctuations and eventually result in new sinkholes. Red clay near the bedrock could be disturbed with seepage deformations which may trigger sinkhole collapses. The karst water level is recovering to normal conditions after the collapsing event. It is unlikely for large scale collapsing events to occur in the near future because of non-fluctuating water levels. However, small scale sinkholes and subsidence may continue due to the disturbance of sediments. Large scale sinkhole collapses may occur again during monsoon seasons. It may take several years to stabilize the soil to normal hydraulic conditions.

Conclusions

Rapid water level rise after a storm event caused a series of collapsing events in Maohe village. Several collapsing events were caused by extreme weather conditions (Gao et al., 2013). Further studies of the relationship between an extreme weather event and sinkhole collapses need to be conducted to prevent such large scale collapsing events in the future.

Compared to limestone settings, the karstification of dolostone was traditionally thought to be relatively weak and the study area has long been listed as a low risk sinkhole area. This study demonstrates that severe damage can be caused by large scale sinkhole collapses in a dolostone karst area.

By monitoring pressure changes of karst water and turbidity of groundwater and locating soil voids and soil disturbances using ground penetrating radar (GPR), it is possible to predict future sinkhole collapses (Jiang et al., 2008; Jiang et al., 2013; Lei et al., 2008; Lei et al., 2010). These approaches are being used to prevent future sinkhole collapses and to reduce the damage caused by the collapsing event.





Figure 5. Hand-dug well with high turbidity and air bubbles (L) collapsed on May 14, 2012 (R).

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KARST LANDFORMS IN THE SARABURI GROUP LIMESTONES, THAILAND

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Abstract

Agricultural development in the Saraburi Province of Central Thailand has increased the demand for groundwater resources. Hydrogeological investigations have been undertaken by Department of Groundwater Resources (DGR) to identify potential zones of groundwater in the karstified limestone of the Saraburi group.

The area is located 120 km north of Bangkok between the cities of Saraburi and Pak Chong in the south, Lopburi to the west, Chai Badan and Nong Pong to the north, and Nakhon Ratchasima to the east. It covers the following districts: Amphoe Pack Chong, Nakhon Ratchasima Province; Amphoe Muang Muak Lek, Khangnoi, Phaputabat, Wong Muang and Chalormphrakiat in Saraburi Province; and Amphoe Moung, Lamsonthi, Phatananikom, Thaluang and Chaibadan in Lopburi Province (Figure 1).

The topography is characterized by mountain ranges, karstic plateaus, and rolling hills of low to medium relief, with low lands in between. The mountainous ridge elevation reaches over 800 m above sea level (ASL), karstic plateaus are developed between 300 and 500 m ASL, and the low lands are at about 100 m ASL. In the karstic plateaus and mountains areas, springs, caves, and dry stream beds exist. In dry periods, some streams in low land areas are dry, but the large rivers continue flowing.

Tropical climate (Monsoon type) with two distinct seasons is characteristic of this area. The dry season begins in October and ends in May, followed by a monsoon season between June and September. Annual rainfall ranges between 1,500 and 2,000 mm and temperature ranges between 20.0°C and 40.7°C.

The area is underlain by the limestone of the Saraburi Group of Permian age. The limestone is exposed as a chain of hills, ridges, and occasionally as mounds which create classic 'tower karst' scenery.

The rainforests, excessive rainfall and widely variable climatic conditions caused a karst landscape and caveforming environment to develop, with streams draining into the limestones from mountain catchments. In this area, the mature karst is locally fringed by tall cliffs that overlook valleys and closed basins. The area underlain by limestone is extensive and rainfall is abundant. Therefore karstification potential exceeds 200



Figure 1. Saraburi Province of Thailand (shown in red).

m vertically. Exokarst landforms are well represented. Various types of karrens, tsingi, small- to medium- sized sinkholes, sinking streams, and closed depressions were identified during site investigation.

A dye study performed in October 2012 indicated the hydraulic connection between a sinking stream and Tham Lumphini Suan Hin Spring, and a water supply well (Well 114) located 300 meters southwest of the spring. Based on the dye study, the protection area for the Well 114 and the spring also includes the closed depressions.

Introduction

Development of land in the Saraburi Province of Central Thailand has increased the demand for groundwater resources. Hydrogeological investigations have been undertaken to determine potential zones of significant accumulation of groundwater in karstified limestone aquifer of Saraburi Group for exploitation.

The area is located 120 km North of Bangkok between the cities of Saraburi and Pat Chong in the south, Lopburi to the west, Chai Badan and Nong Pong to the north, and Nakhon Ratchasima to the east. It covers the following districts: Amphoe Pack Chong, Nakhon Ratchasima Province; Amphoe Muang Muak Lek, Khangnoi, Phaputabat, Wong Muang and Chalormphrakiat in Saraburi Province; and Amphoe Moung, Lamsonthi, Phatananikom, Thaluang and Chaibadan in Lopburi Province.

The topography is characterized by mountain ranges, karstic plateaus, and rolling hills of low to medium relief, with low lands in between. The mountainous ridge elevation can reach over 800 m above sea level (ASL), karstic plateaus are developed between 300 and 500 m ASL, and the low lands are at about 100 m ASL. In the karstic plateaus and mountains areas, springs, caves, and dry streams exists. In dry periods, some streams in low land areas are dry, but the large rivers continue flowing.

Tropical climate (monsoon type) with two distinct seasons is characteristic of the project area. The dry season begins in October and ends in May, followed by a rainy season between June and September. Annual rainfall ranges between 1,500 and 2,000 mm and temperature ranges between 20.0° C and 40.7° C.

Geology

The project area is underlain by the limestone of the Saraburi Group of Permian age. (Ridd et al., 2011) (Figure 2). The carbonate rocks are exposed as a chain of hills, ridges and occasionally as mounds which create classic 'tower karst' scenery.

In stratigraphic order from oldest to youngest, the rock units are the: Phu Phe, Khao Khwang, Nong Pong, Pang Asok, Khao Khad and Sap Bon formations.

Phu Phe Formation (Lower Permian). The carbonate formation consists of pinkish-gray to very dark gray limestone, nodular and tabular chert bands, partly intercalated with slaty shale. Fusulinids and crinoids are present.

The Phu Phe formation is located in the central south part of the project area, and its outcrop covers approximately 68 km² as a ridge with vertical cliffs. The Phu Phe formation is thrusted over Sap Bon and Khao Khad formations of Lower- Middle and Middle-Upper Permian Age. The Phu Phe formation outcrops 25 km East of Saraburi. It is divided in two sections along the Highway No.2 (Mittraphat Road) between the cities of Sap Bon and Khao Phu Phe. The Siam Cement Plant quarry is located in this formation (Figure 3), north of Highway 2.

Khao Khwang/Tak Fa Formation (Lower Permian). The formation is widely distributed in the northern part of the Saraburi area. The formation was deposited in a shallow-marine platform environment (Ridd et al., 2011). From the border between Nakhon Sawan and Lop Buri provinces (the Tak Fa—Ban Mi area) to southern Phetchabun Province (the Nong Phai area), Nakornsri (1976, 1981) established the Tak Fa Formation which is mainly carbonates in the Saraburi Group.

The Khao Khwang/Tak Fa formation of Lower Permian Age is located in the northern part of the project area. The outcrop area is approximately 650 km². It is a karstic plateau with rolling hills of low to medium relief, which continue north with a narrow strip about 25 km long and 4 to 1 km wide (~100 km² – Tak Fa Formation) ridge with vertical cliff and 23 dry-hillside caves. In the latest geological publications/maps the narrow limestone strip belongs to the Tak Fa Formation (Amphoe Ban Mi geological map 1:250,000).



Figure 2. Geological Map of the Project Area (from Ridd et al., 2011).



Figure 3. Geological map with location of karst features.

Nong Pong Formation (Lower—Middle Permian). The Nong Pong Formation is dominated by intercalations of laminated thin-to-thick-bedded shale and thin-bedded limestone with locally developed chert. It occurs widely in the central part of the Saraburi area and it is approximately 670 m thick (Ridd et al., 2011).

The Nong Pong formation is located in the central part of the project area. The area of this outcrop is approximately 700 km². It is a karstic plateau with rolling hills of low to medium relief.

Pang Asok Formation (Lower—Middle Permian). This siliciclastic dominated unit in the Saraburi Group crops out south of the Nong Pong Formation. It is approximately 360 m thick, and consists of interbedded brownish-grey to greenish-grey shale to slaty shale with local sandstone lenses (Ridd et al., 2011).

Khao Khad Formation (Lower—Middle Permian). This unit is up to 1800 m thick and consists of mainly thinto very thick-bedded limestone with chert nodules and locally interbedded argillite, dolomitic shale, siltstone, sandstone and conglomerate. It is distributed extensively in an almost WNW—ESE direction in the Saraburi area. (Ridd et al., 2011).

The Khao Khad formation of Lower-Middle Permian age is located in the south part of the project area. It outcrops as a limestone strip/band oriented NW- SE, 125 km long and 15 km wide. The area of outcrop is approximately 1,875 km². It is a karstic plateau with rolling hills of high relief and some cliffs and ridges.

Sap Bon Formation (Middle—Upper Permian). This is the uppermost unit of the Saraburi Group. The Sap Bon Formation consists of pale-brown to pale-green shale and sandstone interbedded with grey to darkgrey limestone with chert nodules in the upper part. It crops out along the southern margin of the Saraburi Group. Siliciclastic rocks are partly affected by contact metamorphism and altered into slate, phyllite and schist (Ridd et al., 2011).

The Saraburi Group is part of the Indochina tectonosedimentary domain. After the latest Carboniferous, the Khao Khwang platform was developed in the project area. These units are mostly folded, fractured, and faulted across the study area.

Hydrogeology

The availability of ground water in karst aquifer system of the Saraburi Group of Permian age varies widely due to complex geology. This aquifer system has an extensive subsurface network of interconnected joints, fractures, and dissolution/solution cavities as observed in the field during the investigation. These interconnected fractures serve as conduits, leading water from the top of the mountains/karstic plateau to springs. The limestone aquifer system of the Saraburi

Group serve as a major source of groundwater for domestic, industrial, and agriculture uses. At the interface of noncalcareous formations with karstic formations, streams are sinking underground to discharge to spring(s) and cave(s). The availability of water varies during two distinct seasons. During the dry season (October to May) the flow of the springs and rivers/streams diminishes substantially. In the mountains area all the sinking streams were dry. During our field visits in December 2011, 11 springs, one perennial sinking stream, and one perennial cave stream were identified. A network of manmade ponds and lakes has been developed to collect and store surface runoff and the rain water during the wet season. A major portion of the water from the open ponds and lakes is lost due to the high rate of evaporation. Air temperatures are above +30°C for most of the time.

During the rainy season (June to September) flooding occurs periodically, most of the annual rainfall of 1,500 to 2,000 mm has been recorded in this time frame.

Karst Landforms

The karst landforms had been developed by widely variable climate conditions during geologic times. The karstification process is ongoing in the area because of the excessive rainfall and rainforest conditions. In the project area, the mature karst is occasionally fringed by tall cliffs that overlook valleys and closed basins. The area underlain by limestone is extensive. Rainfall is abundant and the karst's vertical potential exceeds 200 m (field observations). Exokarst landforms are well represented. Various types of karren, tsingi, smallto medium- sized sinkholes, sinking streams, and closed depressions are present.

Karrenfields

Karrenfields were identified across the area, the most extensive ones being located in the north of the study area (Figure 4). The second one is two kilometer east of Mu Si Spring, next to a temporary sinking stream (Figure 5).

Tsingi

Tsingi is characterized by vertical rock blades fretted sharp by dissolution (Figure 6). This feature was found on the limestone hills surrounding the karst margin depression, in the central-south section of the project area.

Closed Depressions

The following types of closed depressions were identified in the study area:

Rain pits

Rain pits (1 cm to about 3 cm in size) in the Vicinity of the Waterfall in Khao Khwang Limestone- Huai Nam Sap River (Figure 7).



Figure 4. Karrenfield with Pinnacle (Wat Tham Phrommaloc).



Figure 5. Karren Field – Two km East of Mu Si Spring (Ban Khao Chan Hom).



Figure 6. Tsingi in the Karst Margin Depression (Recharge area of Tham Lumphini Spring).



Figure 7. Rain Pits in the Vicinity of the Waterfall in Khao Khwang Limestone- Huai Nam Sap River.

Kamenitza

Kamenitza in the vicinity of Quarry Spring – Khao Khad limestone (Figure 8).

Sinkholes (Dolines)

Several sinkholes were identified in the northeastern section of the project area. One of the sinkholes was holding thermal water at 37.10° C during field visit in December 2011. The sinkhole is about 10 m in diameter (Figure 9).

Closed depressions

Three large closed depressions and one karst margin depression were identified in the study area. One closed depression oriented NE-SW is located in the vicinity of Ban Khao Takhaeng village, about 15 km south of the area of geothermal anomaly (Figure 10). It is over 2 km long and 1 km wide. A swallet is located at the north end of the depression. During the rainy season, the disappearing stream recharges a temporary karst spring at the base of limestone massif, generating a karst system with temporary flow.



Figure 8. Kamenitza in the vicinity of Quarry Spring – Khao Khad limestone.



Figure 9. Sinkhole with Thermal Water in Vicinity of Wat Tham Phrommaloc Temple.



Figure 10. Closed Depression in the vicinity of Ban Khao Takhaeng Village.

A karst margin depression exists in the recharge area of the Tham Lumphini Suan Hin cave system, which is discussed in Dye Study section.

A third location with closed depressions is situated between the villages of Ban Khao Phra and Ban Khao Loi, about 20 km east of Mu Si Spring (Figure 3).

Springs

In the study area 11 perennial springs were identified (Figure 3). The estimated flow ranges between 0.1 to 400 l/s. The largest spring is the "Hot Well" located in the northern section of the project area, in the villages of Ban Nong Nun - Wat Nam Sut (Figure 11). The estimated flow in December 2011 was about 400 l/s. Based on the geological map, the spring is located in Pleistocene deposit that lie on the top of the Khao Khvang limestone of Lower Permian Age.

Mu Si Spring is located in the south-central part of the project area, in Khao Khad limestone, with a base flow estimated in December 2011 at 150 l/s. The recharge area of both springs (Hot Well and Mu Si Spring) has not been defined (Figure 12).

The Dug Pond and the Tham Lumphini Suan springs have an estimated flow ranging between 15 and 25 l/s. Both springs are used locally for public water supply. The other springs have an estimated flows ranging between 0.1 and 2.0 l/s.



Figure 11. Hot Well (Bat Nong Nun - Wat Nam Sut).



Figure 12. Mu Si Spring.

Dye Study

To characterize groundwater resources in the Saraburi province, a dye study was performed in October 2012.

The Tham Lumphini Suan spring is one of three major springs in the study area, with an estimated flow ranging between 15 and 125 l/s (during the dye study the flow was 106 l/s). A karst margin depression (1.5 km long and 1 km wide) is located in the recharge area of the Tham Lumphini Suan Hin cave system. The south side of the depression is bounded by igneous rock and the north side by a limestone ridge. This limestone ridge is the boundary between the karst margin depression and the closed depression developed along a parallel stream, both being part of the Tham Lumphini Suan Hin cave/resurgence watershed. The karst margin depression ends in a temporary swallet/cave, which in the rainy season, based on the size of the stream bed accommodates a flow up to 1,000 l/s. The cave formed by the sinking stream is linked to the Tham Lumphini Suan Hin cave system (Figure 13).

The primary focus of the dye study was to illustrate the potential hydraulic connectivity of the sinking stream to Tham Lumphini Suan Hin Spring.

Some potential sources for background fluorescence are detergents, bathroom cleaners, pigments for inks and dyes, antifreeze, industrial wastes, naturally-occurring mineral fluorescence, and residual dye from previous studies. Therefore, natural or man-made background fluorescence of the ground water was monitored prior to injection of the dye (background concentration).

A passive dye detector (charcoal bag) was placed at the Tham Lumphini Suan Hin Spring, seven days prior to injection of the dye at the sinking stream. The first charcoal bag for the background portion of the dye was installed on October 6, 2012. The detector was removed for evaluation for background readings one day prior to injection of the dye. A well located in the vicinity of the temple (Well 114) and the right side tributary located downstream the Tham Lumphini Suan Hin spring were monitored during the dye study. No dye was detected in the background charcoal bags. However in the water samples collected at the Tham Lumphini Suan spring before the injection of the dye (background samples), dye was identified as 0.212 ug/l and 0.148 ug/l, respectively. The average of those concentrations 0.18 ug/l was deducted from all the concentrations identified in the water samples collected during the dye study, as a background adjustment.

On October 13, 2012 at 11:00 AM, 200 grams of Uranine (powdered Uranine 40% concentration mixed with a total of 5 liters of water) were injected at the sinking stream. Temperature (24.8°C), pH (8.05), specific conductance (225.7 us), and salinity (0.1ppt) were determined at the time of dye injection.

During the dye study, charcoal bags were installed and water samples were collected at the spring, 687 m away from the sinking stream. Also a charcoal bag was installed about 300 meters downstream of Tham Lumphini Suan Hin Spring, in the right site tributary.

The Uranine was detected in the elutant from all 17 charcoal bags installed and recovered during the dye study at Tham Lumphini Suan Hin Spring. The first arrival of the dye was recorded 20 hours after injection, with the peak dye concentration (6.67 ug/l) being detected on October 15, 2012, 51 hours after injection (flow velocity 35 m/hours). The location of dye injection and monitoring points (spring and Well 114) are shown in Figure 13. Dye detections at the spring and Well 114 are shown on Figure 14.

The peak dye concentration of elutant from charcoal bags recovered from Tham Lumphini Suan Hin spring is 989 Fluorescence Intensity Units (IU), and was detected in the charcoal bag collected 2 days (47–51 hours) after dye injection.

Well 114 (50 m deep) is a water supply well, located 338 meters northwest of Tham Lumphini Suan Hin Spring. Two water samples were collected during the dye study. Dye was detected in the water sample collected on October 15, 2012, 51 hours after injection (flow velocity 19 m/hour), at 6.60 ug/l (after background adjustment), which is the peak dye concentration. A second sample was collected on October 18, 2012, the dye was detected at a concentration of 0.026 ug/l (after background adjustment) (Figure 15).

These results suggest that the groundwater is rapidly traveling between the sinking stream and spring through a fracture system. The direction of ground-water movement is to the northwest.



Figure 13. Topographic map showing the dye injection location and Tham Lumphini Suan Hin Spring.



Figure 14. Breakthrough of Uranine at Tham Lumphini Suan Spring and Well 114.



Southeast ←MMA207 →Northwest **Figure 15.** Interpreted DC resistivity profile.

Based on this dye study, the recharge area of The Tham Lumphini Suan Spring and Well 114 is extended to 4.5 square kilometers towards the dye input location, which also include the closed depression, west to the spring.

Geophysical (Resistivity) Survey

To identify favorable locations for groundwater exploration in the Saraburi Group karstified aquifer system and characterize groundwater resources, an extensive resistivity geophysical survey was performed.

Groundwater can exist in the pore spaces of soil or rock under saturated conditions (i.e. all of the pores, voids, and fractures are filled with water) or unsaturated conditions. It can also exist as underground rivers and lakes in karst environments. Since electricity can move more easily through water than soil or rock, the bulk electrical resistivity of the earth is highly dependent on the presence of water, as well as the salinity of the water. In general, the electrical resistivity of carbonate rock is on the order of thousands of ohm-meters.

The electrical resistivity of soil is on the order of hundreds of ohm-meters, and the electrical resistivity of groundwater is on the order of tens of ohm-meters. These ranges are general estimates, but illustrate the relative difference in electrical resistivity of earth materials.

Direct-current (DC) electrical resistivity was performed along sixty seven (67) profiles distributed throughout the Saraburi Province. Profiles were generally situated along roadsides and were located within various discharge and recharge zones throughout the Province. Data were acquired using a SuperstingTM 8-channel, 56-electrode system. An electrode spacing of 20 meters (m) was used for a total
array length of 1100 m. The dipole-dipole array was used so that lateral variations in electrical resistivity indicative of karst features could be resolved.

Deep (greater than 50 m) low-resistivity anomalies that may be indicative of groundwater were identified. These low-resistivity anomalies were interpreted as potential locations where large amounts of groundwater accumulations, possibly associated with subsurface karst features could be exploited.

Numerous deep (>50 m) low-resistivity anomalies were found along various inverted resistivity profiles. These anomalies are shown in blue in all sixtyseven profiles. One profile (Figure 15) is included herein for illustration purpose. Figure 16 is geologic map showing areas of groundwater potential, with marking low (L), moderate (M), high (H) and very high (VH). These anomalies may correspond to accumulations of groundwater in karst features within the limestone. Other smaller low-resistivity features exist in the profiles indicating that there are extensive groundwater reserves in the area.

Based on the interpretation of the various datasets, the potential for recoverable groundwater was mapped on the geologic map. These zones are marked as low (L), moderate (M), high (H) and very high (VH) (Figure 16). Zones of significant groundwater production potential exist along the edge of the Khorat Plateau. With respect to elevation there is not a strong regional correlation between elevation and groundwater potential, which suggests that the various water-bearing units throughout the region are hydraulically discontinuous, because of geologic structures. This is typical and to be expected in karst terrain due to lack of hydraulic communication between the various subsurface water bearing zones in the region.



Figure 16. Geologic map of groundwater production potential.

Conclusions

The area is underlain by the limestone of the Ratburi Group of Permian age. The carbonate rocks of the Ratburi Group exposed to the east of Chao Phraya Central Plain belong to the Saraburi Group. The limestone is exposed as a chain of hills, ridges and occasionally as mounds which create classic 'tower karst' scenery.

Exokarst landforms are well represented. Various types of karrens, tsingi, small- to medium- sized sinkholes, sinking streams, and closed depressions were identified, during site investigation.

A dye study indicated that there is hydraulic connection between a sinking stream and Tham Lumphini Suan Hin Spring, and a water supply well (Well 114) located 300 m southwest of the spring. Based on this dye study, the protection area for the Well 114 and the spring also includes the closed depression.

Based on the interpretation of the various geophysical datasets, the potential for recoverable groundwater was mapped on geologic map (Figure 16). These zones are marked as low (L), moderate (M), high (H) and very high (VH). Zones of significant groundwater production potential exist along the edge of the Khorat Plateau. With respect to elevation there is not a strong regional correlation between elevation and groundwater potential, which suggests that the various water-bearing units throughout the region are hydraulically discontinuous, because of geologic structure. This is typical and to be expected in karst terrain due to lack of hydraulic communication between the various subsurface water bearing zones in the region.

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CLASTIC SINKHOLE AND PSEUDOKARST DEVELOPMENT IN EAST TEXAS

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Abstract

Pseudokarst development in East Texas is controlled primarily by a combination of suffosion and preferential flow paths, often creating small ephemeral sinkholes but occasionally persistent features develop in more indurated facies. Pseudokarst occurs in Claiborne (Eocene) strata in Angelina, Cherokee, Nacogdoches, Panola, Rusk, San Augustine and Shelby counties. Strata consist of interbedded fine- and coarse-grained clastics with variable cementation and associated permeabilities. Preferential fluid migration along fractures and bedding planes create local voids through suffosion that stope upward to create sinkholes and incised collapse valleys often associated with persistent and ephemeral springs.

GIS-based delineation of pseudokarst sinkholes is complicated in the region by low gradient fluvial systems and extensive anthropogenic overprinting regionally, which create numerous constructional closed depressions. Sinkhole densities coupled with slope analyses indicate clustered regions of pseudokarst development within Carrizo, Queen City and Sparta sandstones. Known pseudokarst caves within the region include features developed along low permeability boundaries where discharge interface features occur. Gunnels Cave is an end member product of natural suffosion processes in East Texas with more than 160 meters of surveyed passage and a collapse sinkhole covering approximately a hectare. Smaller suffosion sinkholes occur along steep gradients but generally remain associated with fracture-controlled flow paths, either forming bypass features or enlarged regions associated with spring discharge. Anthropogenic pseudokarst sinkholes are generally associated with leaky pipelines and focused groundwater recharge from impermeable surfaces and produce local geohazards. Traditionally East Texas is not known for extensive pseudokarst development; however, isolated caves and sinkholes can be locally significant and potential geohazards.

Introduction

Traditionally, East Texas has never been considered a dominant karst region because of the lack of soluble facies in near-surface environments. The region is dominated by Cenozoic clastic sediments associated with shallow marine, lagoonal, deltaic and fluvial deposition (Sellards et al., 1932). Mesozoic carbonate and evaporite strata in the region are deeply buried units that are heavily exploited for hydrocarbon resources (Nichols et al., 1968). These deeper strata inevitably host hypogene karst associated with hydrocarbon maturation and burial diagenesis; however, surficial Cenozoic strata are limited to pseudokarst development, where mechanical disaggregation of grains along focused flow paths creates void space.

Pseudokarst includes any geomorphic features that exhibit morphologies similar to true karst features but have not been formed from solutional processes (Palmer, 2007). Pseudokarst traditionally includes caves, sinkholes and springs but generally lacks karren development. In East Texas, these traditional characteristics have been documented as widespread occurrences, but never in dense concentrations (Atkinson, 2003); however, many small, ephemeral suffusion features commonly occur which act as bypass features for overland flow and direct recharge of shallow groundwater systems. Springs abound in the region as shallow, unconfined aquifer systems discharge along low permeability horizons and where semi-confined and confined aquifer systems discharge vertically to the land surface along preferential flow paths created by brittle deformation.

While pseudokarst development is relatively rare in East Texas compared to true karst development in other regions of the state (Elliot and Veni, 1994), these features do provide unique ecological and culture resources for the region. The Texas Speleological Survey officially reports that thirty seven pseudokarst caves and karst features exist in sixty one counties that cover the greater East Texas region (Atkinson, 2003). This study focuses

on seven counties (Angelina, Cherokee, Nacogdoches, Panola, Rusk, San Augustine and Shelby) (Figure 1), where pseudokarst cave development is primarily limited to coarser grained, sandstone facies of the Claiborne Group (Figure 2), including the Carrizo, Queen City and Sparta formations, while springs and seeps can be found throughout all facies of the Wilcox, Claiborne and Jackson groups where permeability horizons intersect the land surface.

Wilcox Group strata form a heterogeneous series of sandy littoral clays, fluvial sands, lacustrine clays, lignite lentils and deltaic silts, with sand abundance increasing towards the top of the section (Sellards et al., 1932). The Claiborne Group is characterized by a rhythmic series of marine and continental sediment deposits as the Eocene strandline migrated in response to sea level fluctuations (Sellards et al., 1932) and is divided into seven formations (Figure 2) detailed below. Jackson Group strata consist of medium- to fine-grained sands forming thin beds mixed with argillaceous clays and lentils of coarse sands. Tuffaceous material derived from Eocene pyroclastic eruptions is common throughout the Jackson Group (Sellards et al., 1932).

Pseudokarst development in East Texas has only been documented in the Claiborne Group (Stafford et al.,



Figure 1. Digital elevation model of seven East Texas counties encompassing study area. Note the extensive drainage development associated with low gradient fluvial systems in East Texas clastic strata (data from Texas Natural Resources Information System).



Figure 2. Simplified stratigraphic section of East Texas Eocene units. Yellow indicates relative abundance of sandstone dominate facies, while grey represents relative abundance of mudstone facies. Claiborne Group divided into formations.

2010), which consist of the Carrizo, Reklaw, Queen City, Weches, Sparta, Cook Mountain and Yegua formations, in ascending order (Shelby et al., 1968). Carrizo Sand is a massive, very fine- to fine-grained quartz sandstone that is locally cross-bedded and often carbonaceous or ferruginous. The Reklaw Formation is composed of heterogeneous fine- to medium-grained sandstone with abundant glauconitic clay. Queen City Sand is mediumto fine-grained quartz sand that is locally clay-rich and lignitic. The Weches Formation is primarily glauconitic sand with clay interbeds that is often lenticular with local ironstone concretions. Sparta Sand is a very fine-to finegrained massive sandstone that is locally carbonaceous and commonly contains interbeds of silty or sandy clay. The Cook Mountain Formation is primarily clay or marly sand, but locally grades into sheet clays and glauconitic sands. The Yegua Formation is dominated by clay with minor sandstone beds and local concretionary limestone beds; locally it is laminated and contains silicified tuff (Shelby et al., 1968).

Angelina, Cherokee, Nacogdoches, Panola, Rusk, San Augustine and Shelby counties cover 15,146 km² within the Interior Coastal Plains (Wermund, 1996), with elevations ranging from 30 to 230 m asl (Figure 1). Climate in the region is subtropical humid with annual and monthly average precipitations of 1230 mm and 102 mm, respectively (Estaville and Earl, 2008). Average precipitation increases slightly in late fall and spring with slight decreases in late summer. Temperature averages 19 °C, with an average annual lows and highs of 3°C and 35 °C, respectively in January and August (Estaville and Earl, 2008). The region is dominated by mixed pine and hardwood forests with numerous low gradient streams.

East Texas Geology

East Texas is dominated by the deposition of Cenozoic clastic sediments associated with the transgression and regression of coastal strandlines that deposited extensive fluvial, deltaic, lagoonal and shallow marine sediments (Sellards et al., 1932), including strata of the Wilcox, Claiborne and Jackson groups as well as overlying quaternary alluvium and terrace deposits (Figure 3). Structurally, the region is dominated by the Sabine Arch (Figure 4), a basement uplift formed during the late Mesozoic



Figure 3. Simplified geologic map of East Texas study area, with Jackson and Wilcox Groups undivided. Cook Mountain, Reklaw, Yequa and Weches formations of the Claborne Group are undivided. Carizzo, Queen City and Sparta sandstones are presented in contrast because these formations are known to host pseudokarst development (data from Texas Natural Resources Information System).

to early Cenozoic through buckling induced by the Saltillo-St. Lawrence shear system which created the large, low amplitude, anticlinal feature in East Texas and Louisiana (Adams, 1990). The Mexia-Talco Fault Zone borders the eastern and northern portions of East Texas with the Elkhart-Mt. Enterprise Fault Zone dissecting the study area (Figure 4), associated with the Ouachita tectonic front and the Saltillo-St. Lawrence shear system respectively (Adams, 1990). These fault systems have produced abundant near vertical fractures throughout the study area primarily oriented east/northeast, which provide preferential planes for fluid migration.

Stratigraphically the region is dominated by Eocene clastics (Figure 2). Wilcox strata are largely undifferentiated in the region because of heterogeneous fine- to medium-grained sandstones, lacustrine clays, and lignite lenses, with total thicknesses exceeding 500



Figure 4. Simplified structural map of East Texas, including the Sabine Arch, Mexia-Talco Fault System and the Elkhart-Mt. Enterprise Fault Zone (adapted from Martin, 1978). Enlarged area shown on inset map by dashed box outline.

meters in East Texas (Sellards et al., 1932). Although, not known for pseudokarst development in the region, the Wilcox is one of the most prolific groundwater producing units in the region with recharge occurring proximal to the Sabine Arch crest (Ashworth and Hopkins, 1995). Claiborne strata in the East Texas unconformably overlie Wilcox strata and consist of alternating and complexly interfingered coarse-grained sandstones of fluvial and littoral origin with fine-grained sandstones, siltstones and claystones of lagoonal, shallow marine and deltaic origin (Sellards et al., 1932). Generally, coarser-grained facies are more common towards the northern portion of the study area and finer-grained facies occur more abundantly to the south. Claiborne strata consist of a typical rhythmic series of continental and shallow marine facies and ranges up to 450 m thick. Conformably overlying the Claiborne Group, the Jackson Group consists of thin-bedded, shallow marine and beach deposits with zones of argillaceous and tuffaceous clays and tuff, which can reach total thicknesses of 90 m (Sellards et al., 1932).

Within East Texas, previous pseudokarst development has only been documented within the Claiborne Group and specifically within the sandstone facies that were deposited as continental sediments (Figure 3). The Claiborne Group is subdivided into the Carrizo, Recklaw, Queen City, Weches, Sparta, Cook Mountain and Yegua formations from oldest to youngest (Figure 2). Carrizo strata consist of 90% medium-grained sand and 10% sandy clay with the lower portions more heterogeneously cemented by ferruginous material (Sellards et al., 1932). Queen City deposits consist of 70% fine- to medium-grained sand, 22% sandy silty clay, 7% bentonite and glauconite clay and 1% lignite (Sellards et al., 1932). Sparta Sandstone consists of 70% fine- to medium-grained sand, 25% sandy clay, 3% glauconite, 1% limonite and 1% lignite (Sellards et al., 1932). The Carrizo, Queen City and Sparta sandstones were all deposited in continental to littoral environments and are known to host pseudokarst features; however, the more indurated and heterogeneously cemented Carrizo strata appear to be the most favorable for zones for pseudokarst development. Other formations within the Claiborne Group were primarily deposited in marine, littoral and lacustrine environments and reflect higher clay contents (Sellards et al., 1932) which do not appear to promote pseudokarst development in the region.

East Texas Pseudokarst

Pseudokarst development in East Texas occurs as sinkholes, springs and isolated caves in competent facies, while loose, unconsolidated sediments host numerous small suffosion features (Stafford et al., 2010). As with any environment where competent bedrock is overlain by loose unconsolidated material, suffosion features occur as both natural and anthropogenically enhanced structures. Many of these suffosion features act as macropores and fast flow paths for groundwater recharge and bypass features for migration of overland flow to local fluvial systems. True pseudokarst development does occur in the Carrizo, Queen City and Sparta sandstones; some of these features are directly associated with sinkholes, some are effectively modified bypass features and most are associated with spring discharge along permeability horizons. Cave development is limited to competent facies and occurs most commonly in variably cemented zones, where heterogeneous cementation promotes both stable cave development and mechanical disaggregation of clastic grains.

Boatman Cave Complex (Figure 5B) in northern Nacogdoches County represents typical pseudokarst development in East Texas, where a series of springs discharge from the Carrizo Sandstone at a low permeability contact. While only one of the three features at this location meets the true definition of a Texas cave (i.e. length greater than five meters), these small caves are each developed along a vertical fracture plane where laterally migrating groundwater has physically disaggregated sandstone grains near the land surface interface, resulting in three distinct springs converging and discharging into an incised valley. Each spring feature exhibits conduit-like characteristics, with the largest feature actively developing an upward stoping chimney. Most pseudokarst features in the East Texas region exhibit this typical morphology and are not associated with sinkhole development.

At a slightly larger scale, Tonkawa Springs in northern Nacogdoches County is associated with Camp Tonkawa Cave (Figure 5C) which consists of cave development along an enlarged vertical fracture in the Carrizo sandstone. The cave is primarily developed along an east-west fracture that water is discharging horizontally through; a secondary spring inlet converges in the western portion of the cave before discharging to the land surface. The cave was extensively modified when



Figure 5. Simplified cave maps of representative pseudokarst caves in the study area, including (A) Bridges' Cave, (B) Boatman Cave Complex, (C) Camp Tonkawa Cave and (D) Gunnels Cave.

the spring was previously exploited for natural spring water bottling and once powered a grist mill (Brune, 1981); however, much of the original morphology can still be discerned. While some of the four meter tall cave chamber appears to be the result of upward stoping processes, much of it appears smooth and indicative of disaggregation of grains from conduit flow. It appears that most of the cave was originally formed as pressurized fluids were delivered via the fracture plain into the low pressure cavity, creating upwelling flow and producing a morphology, suggesting that the spring associated with cave formation may have an artesian component to it.

An end-member example of this same process occurs in the Carrizo Sandstone in Shelby County with the development of Gunnels Cave (Figure 5D), the largest and most extensive pseudokarst cave currently documented in the region. Gunnels Cave is approximately 70 meters long with over 160 m of surveyed passage and a depth of 12 meters. The cave consists of a linear passage developed along an east-west fracture with one dominant spring and two secondary springs. This suite of springs has formed a lower, northern passage and a higher, southern passage that converge into a single large chamber in the western portion of the cave. The chamber is approximately eight meters tall, almost ten meters wide and encompasses the central quarter of the cave. Throughout the cave, numerous small alcoves and ceiling structures occur suggesting a similar speleogenetic origin as Tonkawa Cave but on a much grander scale. The cave opens to the west, where spring discharge forms an incised valley with additional small alcove caves along its margins, while the eastern portion of the cave connects to a large, steep-walled sinkhole approximately 15 m wide and 50 m long that gently slopes into a watershed covering almost one hectare. Gunnels Cave has long been a local cultural resource, as evidenced by historical graffiti within the cave that dates from the late 19th century.

In contrast to the pseudokarst caves described above, small bypass caves do develop in variably cemented and fractured sandstone facies. Bridges' Cave (Figure 5A) in the western portion of the study area is developed in the Sparta Sandstone where heavily hematite cemented horizons provide both permeability and structural boundaries. In Bridges' Cave, a fluvial system has breached a heavily indurated zone approximately one decimeter thick along an east-west fracture plane, enabling stream flow to descend abruptly several meters. Flow continues to traverse laterally on top of a second indurated layer, where the cave formed over a distance of approximately ten meters. Small alcoves exist within the cave, likely a result of turbulent flow conditions created during intense storm events that rapidly increased the flow through this bypass feature.

GIS Analysis of East Texas Pseudokarst

Analyses of karst terrains have been greatly aided in the past decade by improved digital resources that enable widespread characterization of large regions through GIS (Geographic Information System) techniques; however, the precision of the results are directly proportional to the quality of available data and is no replacement for physical mapping and field studies (Stafford et al., 2008). In East Texas, GIS analyses are complicated by lack of high precision data, extensive vegetation and abundant low gradient fluvial systems. Unlike other portions of the state, LiDAR (Light Detection and Ranging) data does not occur for most of East Texas, with the exception of limited data recently collected through TNRIS (Texas Natural Resource and Information System) in the proximity of the Toledo Bend Reservoir. Therefore, regional GIS analyses are limited to low resolution (10 meter) digital elevation models derived from digitized 1:24,000 quadrangle maps and color-infrared imagery; however, imagery analyses in densely forested regions has very limited application in geomorphic analyses of karst/pseudokarst features.

A sinkhole analysis was conducted on the seven counties of interest in East Texas as an assessment of the feasibility for pseudokarst delineation across the region. Closed depressions were delineated across the study area through DEM (Digital Elevation Model) analysis. A modified tenmeter DEM was created with all depressions filled based on flow accumulation analysis. This modified DEM with filled depressions was then subtracted from the original, unmodified, DEM to identify depressions. The result of DEM raster subtraction identified 2,970 individual closed depressions within the 15,146 square kilometer study area. These identified closed depressions were then filtered to remove features that had a high probability of not being actual pseudokarst features, based on similar filtering methods used in delineation of sinkholes formed by karst processes (Bryant, 2012). Closed depressions that overlapped or that occurred within ten meters of streams and rivers were removed as these features may be associated with fluvial development and do not reflect collapse or suffusion pseudokarst features; however, it is probable that this process also removed some true sinkholes as will all processes involving filtering of data. Closed depressions that intersected or occurred within ten meters of ponds, lakes and surface impoundments were removed because they represent anthropogenic closed depressions associated with development of surficial water resources. Closed depressions within ten meters of roads and highways were removed because it is probable that most of these features are the result of anthropogenic activity associated with infrastructure construction, based on initial field verification. Finally, closed depressions were filtered by surficial geology, where closed depressions within fine-grained, clastic strata (e.g. Jackson Group, Wilcox Group and the Recklaw, Weches, Cook Mountain and Yequa formations of the Claiborne Group) were removed because pseudokarst development has not been documented in these strata within the study area. After filtering to remove all closed depressions not likely to be associated with pseudokarst development, 123 probable pseudokarst sinkholes were defined in the Carrizo, Queen City and Sparta sandstones; however, these features are limited to those closed depressions that cover at least one hundred square meters because of the limitations of tenmeter DEM data. The significant reduction in number of identifiable natural sinkholes from an initially large delineation of closed depressions is consistent with studies in karst terrains where 94% of initially identified features were removed by filtering (Bryant, 2012).

Density analyses of delineated closed depressions and probable pseudokarst sinkholes indicate clustered trends of development. The highest concentrations of closed depressions occur in Wilcox strata and Quaternary alluvium in unfiltered data analyses (Figure 6), which are primarily associated with abundant meandering, low gradient streams and oxbow lake environs in the northeastern portion of the study area (see DEM on Figure 1), with secondary abundant densities occurring in coarser-grained facies in the western portion of the study area. Density analyses of probable pseudokarst sinkholes (Figure 7) indicate that the greatest concentrations occur within the western portion of the study area in Sparta and Queen City sandstones and in the northern portion of



Figure 6. Closed depression density identified through DEM analyses (data from Texas Natural Resources Information System).



Figure 7. Probable pseudokarst sinkhole density identified through DEM analyses after filtering (data from Texas Natural Resources Information System).

the study area in the Carrizo Sandstone. However, these data indicate that Gunnels Cave, the longest pseudokarst cave in East Texas, is truly a unique anomaly occurring in an extremely low sinkhole density region. While density analyses does provide indications of regions of more probable pseudokarst development, the nature of the original data creates a distinct bias that eliminates the ability to discern small-scale pseudokarst features. Low gradient fluvial systems of the area add an additional level of complexity in evaluating whether features are the result of pseudokarst development or are constructional or erosional features associated with fluvial evolution.

In addition to density analyses, slope analyses can be used to further refine probable areas of potential pseudokarst development; however, the same limitations of data apply. By calculating the slope of the ten-meter DEM, regions with high angle slopes can be defined as areas that are beyond the angle of repose for loose, unconsolidated sediments. Therefore, these regions are likely areas where collapse structures or incised valleys occur in more competent facies. By comparing regions where slopes greater than thirty degree occur with regions of high sinkhole density, better refinement of potential area of probable pseudokarst development can be delineated (Figure 8). While these high gradient regions continue to indicate the western portion of the study area likely has



Figure 8. Comparison of steep scarps (slopes >30 degrees) with probably pseudokarst sinkhole density identified through DEM analyses after filtering (data from Texas Natural Resources Information System).

the greatest pseudokarst development and warrants more field study, it also indicates that the Gunnels Cave region should be investigated in more detail. Numerous high angle slopes occur within this region which are likely associated with entrenched valleys and potential spring discharge points that may have formed pseudokarst features in the Carrizo Sandstone.

Conclusion

Pseudokarst development is limited in East Texas and primarily occurs within the coarser-grained clastics of the Claiborne Group, including the Carrizo, Queen City and Sparta sandstones. Pseudokarst features include sinkholes, springs and caves, which are largely associated with the lateral and vertical migration of aquifer fluids along fracture planes which have created preferential flow paths. Permeability boundaries between fine-grained and coarse-grained facies as well as variable ferruginous cementation primarily control the lateral development of pseudokarst caves. Most caves appear to be largely the result of lateral migration of shallow groundwater; however, speleogens in some caves suggest that an artesian component of groundwater flow is likely associated with the formation of larger pseudokarst features.

Density analyses of digital elevation models of the region indicate that pseudokarst development is most extensive in Cherokee and Rusk counties (Figure 7); however, when coupled with slope analyses to identify entrenched valleys, other trends are discernible suggesting that northern Nacogdoches, southern Shelby and northwestern San Augustine counties are also probable sites of more intense pseudokarst development (Figure 8). Although these data are promising, the limitations of ten-meter digital elevation models derived from digitized quadrangle maps presents a large sampling bias based on data quality, but these data do provide preliminary information for focusing field mapping projects to better define the range and extent of pseudokarst within the East Texas region.

Most sinkholes and collapse structures in East Texas are the result of suffusion processes; however, true pseudokarst features are common within the region. Because suffusion features are more common, they provide greater infrastructure and economic concern in the region. Leaky pipelines, poor placement of storm runoff and building construction often focus water through unconsolidated sediments throughout the region resulting in potential geohazards and significant economic loss, attesting to the need for greater public education within the region. In spring 2012, several small earthquakes, up to 4.8 in magnitude, occurred near Timpson, Texas in the study area, which were reported to have induced collapse and sinkhole formation. However, these reports appear to be associated with shallow suffusion features and were likely the result of water from leaky pipelines affected by the ground movement and are not associated with true pseudokarst development in the region.

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CHARACTERIZATION OF KARST COLLAPSE HAZARD BASED ON GROUNDWATER FLUCTUATIONS IN QINGYUN VILLAGE, GUIGANG, GUANGXI, CHINA

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Abstract

In the past decade, sinkhole collapses occurred every year at Qingyun village, Guigang, Guangxi, China. Groundwater fluctuations were thought to cause these collapses. A high resolution real-time monitoring system was established to assess sinkhole hazards in this area. Monitoring of water levels of residential and community wells indicate a water shortage in the shallow karst aquifer, which is greatly influenced by precipitation in the study area. Domestic and irrigation water usage could result in frequent and dramatic changes of water level in the shallow karst aquifer. By comparing with real-time monitoring of the groundwater level in a referenced area with no sinkhole collapsing event, a characterization process was developed to assess sinkhole hazards in the Oingyun village area. Characterization criteria include daily water level fluctuations of karst aquifer, recovery of water level in the karst aquifer, maximum declining rate of water level in the karst aquifer, and sinkhole distribution within 500 m of water pumping activity. The characterization process was then applied to the study area to identify and prioritize areas that are most likely to be affected by human activities. This characterization process could be used by engineers and land-use planners to prioritize water usage and to prevent the development of soil voids and humaninduced sinkholes in active karst areas.

Introduction

Sinkhole hazard assessment has been focused on structural controls, bedrock geology, depth to bedrock, epikarst characteristics, geomorphology, distribution of karst features especially sinkhole distribution, water level to the top of bedrock, pumping rate and duration, N-value of Standard Penetration Test (SPT), soil voids and caves encountered during drilling process, fluid loss and water level changes associated with drilling (Lei et al, 2000; Zisman, 2001; Hu et al., 2003; Waltham et al., 2005; Gao et al., 2005; Gao and Alexander, 2008; Li et al., 2008). However, previous assessments on potentiometric surface and water level changes were used for regional scale assessment of sinkhole hazards. A relatively simple monitoring method is needed to assess potential karst collapses at specific construction or engineering project sites.

In the past decade, sinkhole collapses occurred every year at Qingyun village, Guigang, Guangxi, China. Most sinkholes are round shape ranging from 0.5 - 5 m in diameter and 1 - 5 m in depth. These collapses may affect the ongoing construction of a new natural gas pipeline through the village. The primary goal of this project is to develop a high resolution real-time monitoring system to assess sinkhole hazards along the proposed natural gas pipeline in this area.

Study Area

The study site is located at Qingyun village, Guigang city, 156km east of Nanning, the capital city of Guangxi province (Figure 1). This area belongs to the central -south subtropical monsoon region. Average annual temperature is 21.5 °C and precipitation ranges between 1415.4 to 1731.8 mm per year with 75% occurring during the raining season between April and September.

This is a typical fenglin and tower karst plain. The altitude of the ground surface is about 43.1 - 50.3 m. Land-use is mainly agriculture for crops and small patches of rice paddies. The unconsolidated sediments above bedrock are Quaternary alluvium and colluvium with a thickness ranging between 2.0m and 10.0m. Quaternary deposits are clay and silty clay containing gravels. The bedrock is thick light-gray to dark-gray limestone belonging to Devonian Donggangling formation. Limestone is massive



Figure 1. Google Earth Map of the study area showing sinkhole distribution and natural gas pipeline.

with highly fractured exposures. The study area is also located on the west limb of Tantang - Yunbiao Syncline.

Methodology

No surface water resources exist in the study area. Shallow karst water is scarce and directly affected by precipitation. Groundwater is the only source of water for agriculture, industry, and domestic water supplies. Pumping groundwater has been thought to induce many sinkholes in this area (Figures 1 and 2).

A comparative study of hydrodynamic changes of karst water is conducted in active karst areas with sinkhole collapses and inactive karst areas without sinkholes. Geokon pressure transducers and data loggers were used to monitor real-time water level changes. Based on previous model experiments on sinkhole and soil void formations, measurement intervals need to be less than 30 minutes to capture hydrodynamic controls on sinkhole collapses. Measurement intervals were set at 10 – 30 minutes on this project.

Four monitoring sites were established at existing water wells. Sites 1 and 2 are located in Qingyun village where many sinkholes collapsed in the past. Sites 3 and 4 are located in Jitang village where no sinkhole collapses occurred in the past. The distance between Qingyun village and Jitang village is approximately 8 km.



Figure 2. A collapsed pit caused by groundwater pumping.

Results and Discussion Changes of Hydrodynamic Conditions

Site 1 - Hydrodynamic Changes

Monitoring site 1 is located at a domestic handdug well with a depth of 11.4 m. Water levels were monitored between February 28 and September 2, 2011 with a measurement interval of 30 minutes and 8919 measurements were collected.

Figure 3 shows water level changes in the duration of the monitoring study. The lowest water level is 10.47 m below surface at dry season and the highest water level is 0.41 m during monsoon season. The range between the highest water level and lowest water level is 10.06 m. The thickness of Quaternary sediment is between 6 and 10 m in this area. Therefore, karst water has been fluctuating around the top of the bedrock.

Groundwater level is affected not only by precipitation but leakage of irrigation water for agriculture as well. For example, no rainfall occurred in mid-August and the regional water level declined in the study area. However, the water level at site 1 remains at a higher level similar to the level of monsoon season. Further investigation reveals that significant leakage occurred along irrigation channels during a high demand of water for agriculture in mid-August.

Figure 4 illustrates water level changes caused by pumping activities on August 21. Groundwater was pumped out 4 times between 8:00 and 15:00. A decline of 5.2 m was caused by initial pumping between 8:00 and 10:00. The duration of the subsequent pumping was relatively short (30 minutes) and caused minor decline of the water level at approximately 1 m. It took more than 6 hours for the recovery of the water level after the last pumping. In addition, the rate of water level changes is an important factor triggering sinkhole collapses. The maximum declining rate is 6.58 cm/min and the maximum rate of water level rise is 4.3 cm/min.

Site2 - Hydrodynamic Changes

Monitoring site 2 is located at a domestic hand-dug well with a depth of 6.75 m. Water levels were monitored between December 5, 2007 and January 28, 2008 with a measurement interval of 10 minutes and 144 measurements were recorded each day. Monitoring study occurred during a very dry season with the maximum decline of water level and frequent water level changes caused by water pumping.



Figure 3. The variation of groundwater level of monitoring site 1.



Figure 4. The variation of groundwater level of monitoring site 1 caused by pumping activities on August 21, 2011.

The range of water level change is within 3 m and groundwater is affected mainly by precipitation. For example, rainfall started in the morning on January 25, 2008 and the water level increased from 1.06 m at 8:30 am to 1.65 m at 12:30 pm. In addition, drilling activity associated with the natural gas pipeline construction pumped water out of the well during December 10 and 13, 2007. A sharp decrease of water level was caused by water pumping. Only a limited amount of water was pumped out of this well and water supply is scarce at this site. The maximum declining rate is 2.28 cm/min and the maximum rate of water level rise is 6.85 cm/min during the monitoring period.

Site 3 - Hydrodynamic Changes

Monitoring site 3 is located at a deep well drilled for water supply with a depth of 90 m. Water levels were monitored between February 24 and August 24, 2011 with a measurement interval of 30 minutes and 8784 measurements were collected The lowest water level is 8.48 m below surface during dry season and the highest water level is 1.11 m below surface during monsoon season in the duration of the monitoring study. The range between the highest water level and lowest water level is 7.37 m. Daily water level change is normally less than 4.57 m. Figure 5 shows water level changes on May 21, 2011. Pumping activity is controlled by the storage of water in the water tower. Water level declines drastically during pumping and recovers relatively fast after pumping has stopped (Figure 5).

The rate of water level change is significantly higher at this site because of a higher pumping rate for water supply. The maximum declining rate is 15.26 cm/min and the maximum rate of water level rise is 14.91 cm/ min. Rate changes of at least 10 cm/min occurred 128 times during the monitoring period (Figure 6).

Site 4 - Hydrodynamic Changes

Monitoring site 4 is located at a domestic hand-dug well with a depth of 6.3 m. The distance between site 3 and 4 is 191 m. Water levels were monitored between February 27 and September 2, 2011 with a measurement interval of 30 minutes and 8972 measurements were collected.

The lowest water level is 4.95 m below surface at dry season and the highest water level is 0.26 m during monsoon season. The range between the highest water level and lowest water level is less than 4.70 m. Daily water level change is less than 0.19 m. The maximum declining rate is only 0.65 cm/min on March 19 2011.

Characterization of Sinkhole Hazards Based on Hydrodynamic Conditions

Sinkhole collapses have occurred in Qingyun village every year in the past decade. No sinkhole cases were reported within 500 m of site 3 in Jitang village, even though heavy pumping is a common practice due to limited water supplies in shallow karst aquifers. A comparative study of characterization of sinkhole hazard is based on hydrodynamic conditions observed in these two study areas.

Soil cover thickness, hydrodynamic conditions and sinkhole occurrences were listed in Table 1 based on field investigation and monitoring study. Heavy pumping lasted for more than 6 years at site 3. No sinkhole collapses occurred near this site due to sufficient water



Figure 5. The variation of groundwater level of monitoring site 3 caused by pumping activities on May 21, 2011.



Figure 6. The variation of groundwater level of monitoring site 3.

supply in the deep karst aquifer. Site 1 and 2 are handdug wells to shallow karst water. Pumping activity in this area can cause rapid water level fluctuations and slow recovery due to scarce water supply in shallow karst aquifers, which may cause soil piping and soil void formation and eventually trigger sinkhole collapses.

By comparing hydrodynamic conditions between Qingyun village and Jitang village, characterization criteria of sinkhole hazards are as follows:

 Daily water level change and the recovery of water level after pumping: Daily water level changes reflect the amount of groundwater withdrawn, and the recovery of water level after pumping is related to the amount of water storage and supply in the karst aquifer. The study area is divided into 3 sinkhole hazard areas:

Low risk area: daily water level change is less than 1.0 m and the recovery of water level is less than 5.0 hours after pumping.

Site	Thickness of soil coverage (m)	Rate of declining water level	Time of water level recovery	Daily water level change (m)	Maximum water level change (m)	# of sinkholes within 500 m	Connection between karst and Quaternary
		(ciii/min)	(nour)				aquiters (Y/N)
1	8.0	6.58	10	4.4	10.06	3	Y
2	6.0	6.85	12	0.30	2.6	4	Y
3	1.5	15.26	0.5	4.57	7.37	0	N
4	1.8	0.65	5.0	0.8	4.7	0	N

Table 1. Soil coverage and hydrodynamic conditions in the study area.

Intermediate risk area: daily water level change is 1.0 - 3.0 m and recovery of water level is 5.0 - 10.0 hours after pumping.

High risk area: daily water level change is greater than 1.0 m and the recovery of water level is greater than 10.0 hours after pumping.

(2) Maximum declining rate of karst water level: Sudden water and air pressure changes within karst fractures and conduits have been associated with sinkhole collapses in many cases. Model experiment based on geologic settings in several karst areas in Guangxi reveals that severe soil damage would occur when the declining rate of water level is above 180 cm/min. The rate of water level change in the study area is way below the critical value of 180 cm/min. Therefore, there is no immediate threat of sinkhole hazard.

More quantitative assessment is needed based on the above criteria. Pumping activities along with ongoing natural gas pipelines may cause significant changes of hydrodynamic conditions in the study area. Real-time monitoring of daily water level changes, water level recovery, and the rate of water level changes will provide guidelines and limit water pumping activities to reduce potential sinkhole collapses.

Conclusions

A high resolution real-time monitoring system was established to assess sinkhole hazards in this area. Monitoring of water levels of residential and community wells indicate a water shortage in the shallow karst aquifer, which is greatly influenced by precipitation in the study area. By comparing with real-time monitoring of groundwater levels in a referenced area with no sinkhole collapsing event, a characterization process was developed to assess sinkhole hazards in the Qingyun village area. Characterization criteria include daily water level fluctuations of karst aquifer, recovery of water level in karst aquifer, and maximum declining rate of water level in karst aquifer. The characterization process was then applied to the study area to identify and prioritize areas that are most likely to be affected by human activities. The study area is divided into 3 sinkhole hazard areas based on daily water level changes and the recovery of water level after pumping. Realtime monitoring of daily water level changes, water level recovery, and the rate of water level changes will provide guidelines and limit water pumping activities to reduce potential sinkhole collapses due to increased water demand caused by the construction of a natural gas pipeline through Qingyun village.

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INVESTIGATIONS OF LARGE SCALE SINKHOLE COLLAPSES, LAIBIN, GUANGXI, CHINA

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Abstract

A series of sinkholes collapsed at Jili village and Shanbei village, Laibin Guangxi, China in June 2010. A large underground stream exists in the north-south transect of the study area and passes the collapse site. Preliminary investigations revealed that extremely heavy rainfall between May 31 and June 1 2010 may have triggered this collapse event. The precipitation, as high as 469.8 mm within one day, was a record high in the study area. A long period of drought in 2009 followed by extremely heavy rainfall along with cave roof collapse may have caused the collapse event on June 3 2010. The "water hammer" effect and collapsetriggered earthquakes caused severe ground failure and fractures in residential houses and Jili Dam. Several collapse events were caused by extreme weather conditions in Guangxi over the past few years. Further studies of the relationship between extreme weather events and sinkhole collapses will help minimize the damage or impact to human infrastructure by avoiding areas susceptible to collapse or by designing infrastructure to better withstand subsidence.

Introduction

On June 3 2010, four extremely large sinkholes collapsed at Jili village and Shanbei village, Laibin Guangxi, China. These sinkholes expanded and merged to form a 200 m long collapse zone. Many ground failures and fractures occurred in the area. An area of 0.4 km² was impacted by the collapse event. Because the collapses occurred in areas with a high density of population, initial investigation results reveal severe damage to residential houses. A total of 130 families, more than 600 people, a dam and a highway were impacted by the collapse event. This paper discusses the geologic background, possible mechanism of sinkhole collapses, and future studies of sinkhole hazard assessment in the study area.

Geologic Settings

Jili village is located in central Guangxi province, a highly active karst area containing many karst features such as sinkholes, springs, karst windows, caves, and conduit systems (Figure 1).

The study area is a typical fengcong and fenglin karst area with isolated and dissolved hills and valleys. The unconsolidated sediments above bedrock are Quaternary alluvium and colluvium. Quaternary deposits consist of silty clay, clay containing gravels, and clay. Karst bedrock units belong to the middle Carboniferous Huanglong Formation (C_{2h}) and Nandan Formation (C_{2n}). Rock types include thick light-gray limestone, gray fossiliferous limestone, dolomite limestone, siliceous and fossiliferous limestone, limestone containing gravels,



Figure 1. Geographic location of Laibin.

and dolostone. Non-karstic bedrock units belong to the lower Cretaceous Yongfu Formation (K_{2y}) . Rock types include reddish arkosic sandstone and mudstone.

Surface water and Quaternary groundwater are scarce in the study area. Groundwater resources include karst water within bedrock matrix, fracture, and conduits and a limited amount of Quaternary water in porous sediments. Fairly large springs exist in the area, which are recharged through sinkholes, active karst fractures and conduits. Three large springs with discharge rates of 100 - 1336.5l/s are located near Liangxian. Approximately 100 - 400m³/day of water discharges out of drilled holes. Hongshui River, located 16 km north of the study area, marks the regional level for base flow, which receives water from most base flow groundwater in the study area.

Preliminary investigations of sinkholes, subsidence areas, and large springs reveal that a large cave stream exists in the study area at nearly a N - S orientation. The three large springs may serve as discharge outlets of the cave stream. The cave stream passes through the sinkhole plain and discharges to Chenglong Creek, a tributary of Hongshui River.

Sinkhole Distribution

Preliminary investigations revealed that extremely heavy rainfall between May 31 and June 1 2010 may have triggered this collapse event (Figure 2). The precipitation, as high as 469.8 mm within one day, was a record high amount in the study area (Figure 3).

Two earthquakes at Richter scale of 1.9 - 2.0 were recorded on June 1 by the Guangxi Bureau of Earthquake Investigation. The first sinkhole collapsed at 9:00 am on June 3, 2010. Four extremely large sinkhole pits formed within 3 hours. These sinkholes expanded and merged to form a 200 m long collapse zone (Figure 4). Walls of these sinkholes are not stable and these sinkholes kept growing after the initial collapse (Figure 5).

Earthquakes which occurred on June 1 were probably caused by cave roof collapses. The "water hammer" effect caused by cave roof collapse can release a pressure surge to the karst conduit system and sediments overlying the karst conduit, causing severe soil damage and subsequent collapses (Lei et al., 2010;



Figure 2. Daily precipitation between September 2009 and August 2012 in the study area.









Figure 5. Sinkhole no. 3 with unstable walls.

Lei et al., 2013). Earthquakes and the "water hammer" effect may also have caused fractures in many houses and the Jili Dam (Figures 6 and 7).

Conclusions

Rapid water level rise after the storm event caused a series of sinkhole collapses in the study area. Several collapse events were associated with extreme weather conditions in Guangxi over the past few years (Lei et al., 2013). Further studies of the relationship between extreme weather events and sinkhole collapses will help minimize the damage or impact to human infrastructure by avoiding areas susceptible to collapse or by designing infrastructure to better withstand subsidence.

An on-site investigation revealed that initial collapses occurred during heavy rainfall. The precipitation, as high as 469.8 mm within one day, was a record high amount in the study area. A long period of drought in 2009 followed by extremely heavy rainfall along with cave roof collapse may have caused the collapse event



Figure 6. Ground failure and damage to a residential house.



Figure 7. Fracturing through ground and houses.

on June 3 2010. Cave roof collapse may trigger a "water hammer" effect in the karst conduits. The "water hammer" effect can cause severe soil damage and trigger subsequent collapses (Lei et al., 2010; Lei et al., 2013). Soil disturbance may change hydraulic gradient, which can cause water level fluctuations and eventually result in sinkhole collapses.

Recommended techniques for assessing sinkhole hazards include: potentiometric mapping, locating areas of disturbed soil and soil voids using ground penetrating radar (GPR), monitoring karst groundwater pressure changes, sinkhole inventories, and tracer test of surface water and groundwater interaction. These approaches are being conducted in other areas to prevent or forecast sinkhole collapses and to minimize the damage caused by sinkhole collapses (Jiang et al., 2008; Jiang et al., 2013; Lei et al., 2008; Lei et al., 2010).

Karst water levels are recovering to normal conditions after the collapse event. It may take several years to stabilize the soil to normal conditions. A 10 m x 10 m soil collapse area was recently discovered in the south portion of the study area. A donut shaped subsidence area formed around the new collapse site. The diameter of the subsidence area is 100 m with ground failures and fractures formed inside the subsidence area. This area is located directly above the subterranean stream. Large scale sinkhole collapses may occur again during monsoon seasons. Residents in Jili village and Shanbei village may need to be relocated to a safer place. Jili Dam and Guibei highway need to be evaluated for further damage.

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MAPPING FLOOD-RELATED HAZARDS IN KARST USING THE KARSYS APPROACH: APPLICATION TO THE BEUCHIRE-CREUGENAT KARST SYSTEM (JU, SWITZERLAND)

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Abstract

The city of Porrentruy (JU, Switzerland) is vulnerable to flooding from karst water draining the system of the Beuchire-Creugenat. Major flood events in 1804 and 1901 led to heavy damages throughout the city and its vicinity. Furthermore small-scale flood events have been recorded five times in the last 30 years - each resulting in substantial costs.

The Beuchire-Creugenat karst system is characterized by a perennial outlet (the Beuchire spring) and several overflow outlets (among which the Creugenat temporary outflow is the most significant one) where the discharge rate often exceeds 15 m^3 /s. The ratio between rainfall intensity and discharge rate of the overflow springs is not closely correlated. Therefore, the discharge rates and the conditions at which a certain overflow becomes active could not be assessed without a comprehensive understanding of the karst system behavior. Thus, the establishment of effective flood risk management measures remains significant challenge.

In order to assess similar flood events and to determine the most flooding vulnerable areas, the KARSYS approach has been applied to the Beuchire-Creugenat karst system. A detailed geological 3D model of the study area has been built in order to reproduce the aquifer base geometry, the extension of its expected saturated part(s) and the position of the main vadose flowpaths "drainage axes". This approach enabled the catchment area delineation by combination of subterraneous drainage axes. The comparison of the discharge time series of the main springs and the relevant rainfalls (~10-year series) provides sufficient implications for understanding and consequent reproducing of threshold functionality of the karst system exposed to flooding due to rainfall events. A relationship could be established between rainfall intensity/frequency (return period) and the corresponding elevation of the groundwater level within the karst conduits (or respectively, the relevant spring discharge rates). The known overflow springs have been added in the 3D model. The areas where (and when) karst groundwater is expected to reach the ground surface during extreme high-water events could be identified as potential overflow springs. Such draining sensitive areas have been delineated and mapped according to the calculated return period of multiannual, 30- and 300years flood events and the relevant maximum discharge rates at the main outlets have been assessed.

Introduction

Flood events in the Swiss Jura Mountains are dampened/ enhanced by karst overflows. The flood event of August, 1st 1804 in Porrentruy (JU) is a the largest known event of a flashy karst inundation (Prudhomme 1804).

Associated discharges reaching 100 m³/s have been reported—four or five times larger than big flood amount recorded for this karst system. Similar events were recorded in 1901 and 1910 (Figure 2). In addition to these events smaller - but still extreme events - occurred five times in the last 30 years (BG 2011). The most recent well documented flood event occurred on August 9th, 2007. The Creugenat overflow peak discharge approached 20 m³/s.

The local authority (administration of the Jura canton) has to plan protective measures to diminish the potential damages from flooding to maximum extent possible. The understanding and prediction of such extreme situation is then required for assessing the probable occurrence and the intensity of such flood events, in order to manage areas threatened by flooding.

Two local civil engineer offices and the Swiss Institute for Speleology and Karst Studies (SISKA) - as a karst specialized institution - were asked to provide a model for the study region. The assessment was conducted applying the KARSYS approach (Jeannin et al. 2012) expanded with some hydraulic considerations. The aim was:

- To understand the significant characteristics of the groundwater flow routes and the position of the karst water table for various recharge scenarios. Recharge events with return periods ranging between 30- and 300- years were considered.
- To determine and map areas which are the most vulnerable to flooding assessed by the potential overflows of karst groundwater and to assess the related discharges at the outlets and in a next work within the subterraneous flowpaths.

The locations where karst groundwater is expected to reach the most forward ground surface are the most vulnerable to flooding. Having assessed the respective catchment areas of the underground tributaries, discharge rates can be assumed within the limitations of the project.

Context

The geological context refers to the Tabular Jura which is slightly folded and intersected by numerous strike faults (Kovács 2003, Sommaruga 1997). The Beuchire perennial karst spring emerges in the center of Porrentruy (see Figure 1) at an elevation of 423 m a.s.l. (meters above sea level). Its mean annual discharge is 800 L/s.

The spring reaches 1600 L/s at high water flow and may discharge more than 3 m³/s during a flood event. Groundwater flow moves through the Malm aquifer which is composed of alternating units of Upper Jurassic limestone and thin layers of marls. The Malm aquifer is underlied by a thick marl formation (Astartes marls, Laubscher 1963). This aquifer reveals to be the most karstified one in the region. Although the underlying marls are qualified as impervious, the Malm's aquifer water exchanges with the lower aquifer are highly likely through discontinuities in the marls.

Upstream of the Beuchire spring, the Creugenat temporary outflow (see Figure 3) emerges at 451



Figure 1.The Beuchire karst spring is located in the city of Porrentruy (JU) in Northwest Switzerland.

m a.s.l. It becomes active only at high water stage. The global discharges in the city of Porrentruy may reach a maximum close to 30 m³/s (Grétillat 1996). Further upstream, at an elevation of 465 m a.s.l., lies the estavelle of Creux-des-Prés which functions as a second temporary outlet of the system and becomes active only during very high water stage (see Figure 4). The discharge series of the Beuchire spring and pressure series of the Creugenat temporary outflow have been measured at hourly time steps, respectively between 1998 to 2004 and 1998 to 2008. In addition to these three main springs, a series of minor temporary outlets do exist. Unfortunately they are badly documented due to infrequent activity (Les sources, Libecourt, etc.).



Figure 2. The flood event of 1910 in Porrentruy. Inundation is the result of extreme karst aquifer discharge through the Creugenat (Archives de la Bourgeoisie de Porrentruy, JU).



Figure 3. The Creugenat overflow in 1934. First pumping test to dry up the siphon (picture A. Perronne).

Although the Beuchire spring and the Creugenat overflow have been fairly studied (Bouvier 2006; Grétillat 1996, Hessenauer and Meury 2002,Kovács and Jeannin 2003, Lièvre 1915, Lièvre 1940, Schweizer 1970, Monbaron 1975, etc.) available data remained limited and some questions did not find a clear solution. None of these studies describes in details the potential catchment boundaries and their possible changes in relation to the water stage. In this context the KARSYS approach (Jeannin et al. 2012) was applied to estimate the geometry of the aquifer(s) boundaries, to delineate groundwater body(ies), and to assess the functioning of the Beuchire spring and the Creugenat overflow.

This approach was assessed for low, medium, high and extremely high water conditions.

A 3D model to assess the aquifer geometry

In order to assess the geometry of the aquifer, a 3D geological model focusing on the aquifer basement (i.e. Astartes marls) was established for the area of interest (14 km by 9 km) at a scale close to 1/25,000 (see Figure 5) to meet the requirements of a pragmatic issue. This was possible thanks to an extensive compilation of all existing data relative to geological information (borehole logs, maps, cross sections, tunnel profiles, dye tracer tests results, etc.) and the previous work of Kovács 2003, which provided a strong basis of documentation.

Once the geological model has been established and the data checked, the hydrological features have been implemented within the 3D model. These features consist of major perennial springs as well as minor temporary ones. Then, the extension of the saturated part of the aquifer was assessed by following the KARSYS approach.

This approach assumes that at low water stage, the top of the saturated part of a karst aquifer is close to horizontal and can be represented within the model by a horizontal plane at the main perennial spring elevation (the Beuchire spring in the present case). The portion of the aquifer located underneath that horizontal plane should be close to the volume extension of the karst phreatic zone.



Figure 4. SW-NE profile of the Beuchire catchment and projection of the overflow outlets. The real distance between the Beuchire spring and the Creugenat temporary overflow is 4,3 km. The Creugenat overflow and the Creux-des-Prés temporary overflow are 1.45 km appart.



Figure 5. Illustration of the 3D geological model of the aquifer basement from the Beuchire karst system intersected by geological cross-sections. This was modeled using GeoModeller® (Intrepid Geophysic). The main spring is on the front of the model.

This process was applied to the model and gives the following results (Figure 6).

The process identified two unconfined groundwater bodies (GWB A and B) separated by a geological threshold which top elevation is at 440 m a.s.l. This fact also predetermined the volume extension and surface areal extension of each GWB, 21 km² (A) and 6 km² (B) and taking into account the assumed limestone porosity (~1% in a first approximation) the water content could be estimated; respectively as 6.4 Mm^3 and 2.9 Mm³ at the low water stage.

Knowing the location and volume extension of the saturated parts of the aquifer, the catchment area feeding each of these groundwater bodies could be delineated. Then, following the shape of the aquiclude topography, sub-catchments and their respective "drainage axes" were rendered. Drainage axes are recognized as vadose ones if they are located above the saturated zones. They are assumed to be developed at the bottom of the aquifer along the dip of the basement. Phreatic passages located within the saturated zones are "drainage axes" linking input points into the phreatic zone to the main drainage axis linking of the Creugenat temporary outflow and the Beuchire spring. Phreatic flowpaths are mainly horizontal and *a priori* follow the shortest hydraulic distance to the outlet(s).

The model result for low water stage is presented in Figure 7.

The total groundwater catchment area in low water situations is thus estimated at about 79 km². GWB A flow is driven toward the Beuchire spring and GWB B flow is drained toward the Bonnefontaine spring, which is not visible in the figures for this paper.

Assessing the system at high water stage (hydraulic gradients within the conduits)

In the next step, the hydrology of the system is assessed for high water conditions, *i.e.* when overflow springs (Creugenat and Creux-des-Prés) successively become active according to the rise of the groundwater head in the conduits.

The discharge data from the Beuchire spring are compared with the head data recorded at the Creugenat temporary overflow (see Figure 8).



Figure 6. Model identification of two main groundwater bodies (GWB), A = Beuchire GWB (elevation 423 m a.s.l), B = Bonnefontaine GWB (elevation 438 m a.s.l).



Figure 7. Model identification of the main underground vadose (yellow) and phreatic (blue) flowpaths of the Beuchire-Creugenat karst system at low water stage.

The graphic indicates that:

- As the Beuchire spring discharge remains lower than 700 L/s, the water level at the Creugenat overflow does not react (~438 m a.s.l). This indicates that both systems are disconnected by a threshold (a) situated at this elevation.
- As the discharge exceeds 700 L/s the water level progressively rises up and shows a threshold (b) at 443 m a.s.l corresponding to a discharge of 1,450 L/s
- As the discharge exceeds 1,500 L/s the water level at the Creugenat rises up a second time until it reaches the output elevation (c) at 451 m a.s.l corresponding to a discharge of 2,250 L/s.

Contrary to previous studies (Grétillat 1998, Hessenauer and Meury 2002) which considered threshold (b) as a first activation of the Creugenat overflow, this analysis indicates that the Creugenat becomes active only when the Beuchire spring discharge exceeds 2,250 L/s. Then threshold (b) indicates that an intermediate overflow (or large storage) must exist in between (at around 443 m a.s.l). This could be a karst conduit or an outlet to the ground surface.



Figure 8. Comparison of the hourly pressure data recorded at the Creugenat overflow and the hourly discharge values of the Beuchire spring during flood (grey) and recession (red) events (2002-2004). Model 1 simulates a threshold discharge at an elevation of 437 m a.s.l at a suggested distance of 1,300 m downstream from the Creugenat. Model 2 simulates an ideal function of the spring discharge using a k*S of 28 m3/s (conduits diameter of ~2.7 m) and a straight distance of 4,000 m.

Assuming that the flows to Beuchire spring may follow the usual head-loss laws in pipes (Darcy-Weisbach type), the relation can be simulated using the following equation:

$$Q = k'S * \sqrt{\frac{dH}{dL}}$$
 (Eq. 1)

With Q $[m^3/s]$, k*S =f(section m²) $[m^3/s]$, dH/dL = hydraulic gradient [m/m]. Application of this law is plotted on the chart (models 1 & 2, Figure 8).

Model 1 suggests that the hydraulic connection between the Beuchire spring and the Creugenat overflow is active when the water elevation in the conduits ranges from 438 to 443 m a.s.l. Below this value the system follows a head-loss equation. However, this model cannot explain the observed relationship of the water level between 443 and 451 m a.s.l.

Therefore, model 2 depicts a hypothetical outlet at threshold (a) downstream from the Creugenat overflowi.e. at an elevation of 443 m a.s.l. The head-loss equation is valid for an outlet located at a distance of 4,000 m and with a k'S of 28 m³/s (considering an average conduit diameter of 2.7 m) to reproduce the observed trend.

Previous observations led to the hydraulic schemes of the karst system presented in Figure 9 that depends on the groundwater level elevation. This provides a set of hydraulic gradients which can be implemented in the 3D model at various high water flow conditions. One result is displayed on Figure 10 where the gradients correspond to a usual overflow of the Creugenat (average annual flood event) at high water stage. Upstream of the Beuchire spring the hydraulic gradient strongly increases until it reaches the Creugenat overflow (the slope of the gradient is close to 0.7%). If the water level still increases the Creugenat overflow becomes active and the gradient does not rise significantly ahead. In Figure 13 areas that are susceptible to flooding during such events are mapped in yellow.

Similar scenarios could be established for two larger flood events: the 30- and the 300- years flood events. The August 2007 flood event, defined as a 30 years event (by analysis of the IDF curves, BG 2012) is characterized by the Creux-des-Prés overflow. Between the Beuchire spring and the Creugenat overflow the hydraulic gradient remains comparable to the value encountered above



Figure 9. Sequential evolution of the hydraulic gradient within the Beuchire-Creugenat karst system (i.e. the conduits) for an average annual flood event reaching the Creugenat overflow. The profile of the conduits is here supposed. Processes are the following:

- The groundwater level at the Creugenat overflow is independent of the Beuchire spring discharge oscillations;
- 2. The water level at the Creugenat overflow is controlled by the threshold (a);
- At 443 m a.s.l. the activation of an additional conduit (or a perched spring) show a lag in the water level elevation rise at the Creugenat overflow;
- 4. The rise of the groundwater level at the Creugenat overflow depends on the Beuchire spring discharge. At 451 m a.s.l the Creugenat overflow is now flowing!

($\sim 0.7\%$). Upstream of the Creugenat overflow, the hydraulic gradient of the groundwater flow in the conduits is here fixed by Le-Creux-des-Prés outlet and by the bottom of the valley (several outlets were active during the 2007 flood events providing some arguments to fix

the gradient): its slope is approximately 1% extending the groundwater bodies as pictured in Figure 11. The areas which are vulnerable to flooding when such type of flood event occurs are filled in orange in Figure 13.

For a 300-year flood event (as the flooding in 1804) the hydraulic gradient within the conduits does not change between the Beuchire spring and the Creugenat overflow (0.7%) and between the Creugenat and the Creux-des-Prés overflows (\sim 1%). Upstream of the Creux-des-Prés we allocated the gradient on the basis of the more elevated outlets (higher than 500 m a.s.l) and the shape of the versants. The gradient is therefore approximately 1.5%. Surfaces that are here vulnerable to flooding are the more extended ones (labeled in red in Figure 13).



Figure 10. Model prediction of the extension of groundwater bodies (GWB) A and B during a flood event reaching the Creugenat overflow (=multiannual occurrence =case 4 in Figure 9). Water from GWB B overflows over two passes and contributes to the discharge of the Beuchire spring.



Figure 11. Model prediction of the saturated groundwater bodies extension in the Beuchire-Creugenat karst system during a flood event reaching the Creux-des-Prés overflow (~30-year flood event).



Figure 12. Model predicted storage in the aquifer (i.e. the karst conduits) and its development due to groundwater increase within the karst system for the respective flood events (average annual, 30-year flood events and ~300-year flood events). The associated volumes refer to water potentially involved in the floods (1.7 Mm3 for an average annual flood event, 4.4 Mm3 for a 30-year flood event and more than 6 Mm3 for a 300-year flood event).

In addition to these gradients some further temporary springs were observed previously in the field and reported by Bouvier 2006. They were used as controls for the prediction of potential outlets based in the 3D model.

Considering the respective values of the hydraulic gradients during these events, it is possible to estimate the associated volume of groundwater involved in the floods (or at least which should flow within the system). This implies to know or at least estimate a value of efficient porosity (i.e. density of conduits / volume of flooded

aquifers) which could be taken as a first approximation about 0,5% (in the swiss Jura, according to Bauer et al. 1980, Burger and Pasquier 1984). This value may be refined in the further development of the project.

Mapping the flooded areas

According to the previous model results it is possible to map surface areas which could be affected by the potential flood events. The results for the Beuchire-Creugenat catchment are displayed in Figure 13. The next step in flooding hazard characterization is the expected drainage





Figure 13. Flood hazard map of the Beuchire-Creugenat catchment area. Color code refers to the considered occurrence: average annual flood event, 30-year flood event, 300-year flood event). Filled areas have to be considered as potentially exposed to flooding or at least as potentially impacted by an overflow from a temporary outlet. The interpreted drainage axes (both vadose and phreatic) are also displayed on this map.

axes discharge rates assessment for each type of flood event. This is possible once the catchments of these have been clearly delineated as well as their respective recharges. This assessment will be conducted in the second part of the project by the establishment and the use of a hydraulic model. In the present paper only the maximum discharge of the respective outlets (permanent and temporary ones) was assessed for a average annual flood event and a 30 years flood event. Such models are useful for designing future construction or hydraulic works.

Maximum expected discharges at the outlets

Discharge of springs usually increases as the level of the groundwater increases within the system until one overflow spring becomes active. Then, even if the groundwater level still rises in the conduit, the discharge of the lower spring does not increase significantly. Based on that principle, it is possible to estimate the maximum expected discharges at the Beuchire spring and the Creugenat overflow.

Regarding the Beuchire spring, the maximum discharge is limited by the overflowing of the Creugenat outlet (Figure 8). Even if the groundwater level in the karst system still increases the Beuchire spring cannot discharge more than 3,5 m3/s.

The maximum discharge rate at the Creugenat outlet can be estimated from the discharge of the stream in the city of Porrentruy as soon as the Creux-des-Prés overflow becomes active. Comparing the last 2007 flood event with a 30 years flood event and knowing the moment when the Creux-des-Prés overflow discharged - it was estimated that the maximum discharge rate at the Creugenat overflow is about 18 m3/s.

Discussion

In June 2012 a collapse appeared in the middle of a road, on a straight line between the Beuchire spring and the Creugenat overflow (Figure 14, ISSKA 2012). The pit located at an elevation of 443 m a.s.l - reached the depth of 8 m and at that time its bottom was dry. This collapse gave the SISKA the opportunity to install a pressure sensor with the aim to survey an eventual presence and oscillations of the groundwater within the pit. The recorded data (only few weeks available) show periodic rises of the groundwater with a maximal elevation of 438.6 m a.sl (~4,5 m below the surface) that led to a





Figure 14. The new collapse of the community of Courtedoux gave access to a 8 m deep pit. The bottom of the pit was monitored with a pressure sensor. The recent data allowed validation and improvement of the Beuchire-Creugenat karst system model functionality.

deepening of the collapse. The recorded oscillations of the groundwater are consistent with the previous interpretation related on Figure 9.

In addition to this flood event, new piezometric data were collected from a borehole (POR3) located in the vicinity of the Creugenat overflow. First comparison of these data with the recorded oscillations of the Creugenat overflow provides new calibration elements that improve the model functionality. Currently, a series of simulations are being conducted using the actual release of SWMM (Storm Water Model Management, Rossman 2004) to approach the karst conduits and to fix the thresholds and the related storage within the aquifer.

The identification of the main drainage axes will lead to the delineation of sub-catchments areas within the system catchment. When they are defined their respective recharges will be assessed and extrapolated to estimate the maximum discharges which could be expected within the conduits. These simulations are expected to produce relevant results that will improve the modeling of the flood hazards in the region of the Beuchire-Creugenat karst system. They will also bring quantitative elements to design future construction and hydraulic works.

Conclusion

The characterization of the flood hazard in the vicinity of the city of Porrentruy - vulnerable to flooding by the Beuchire-Creugenat karst system discharge- was conducted by applying the KARSYS approach. A 3D geological model depicting the aquifer basement has been established and progressively improved with field data and literature documentation. By following the hydraulic principles in karst hydrology, it was possible to sketch the vadose and the phreatic zones as well as the main suspected flowpaths. The catchment area of the system has been delineated and divided in basin-units aiming distinguishing their recharge contribution at the next stages of the study. By using the available discharge data of the Beuchire spring and head measurements of the Creugenat overflow it has been possible to determine a thresholds functioning of the system and to approach the geometry of the groundwater hydraulic within the conduits in the high water stage and to delineate where water is susceptible to reach the ground surface and to enhance the risk of inundation. Areas on ground surface may be affected by flooding depending on the occurrence of the mapped considered events (average annual flood event, 30-year flood event, 300-year flood event). Furthermore successive activation of the outlets and their associated discharges are now predictable.

Recent integration of piezometric data from a borehole in the vicinity of the main temporary outlet (Creugenat) and the more recent instrumentation and observations in the collapse at Courtedoux (which appeared in June 2012) brought new indicators to control and improve the established model. Current simulations using SWMM and based on these new data may provide new elements in conduit geometry characterization and to improve the hydrological model. The last could be applied in further hydraulic planning, especially in estimating the groundwater discharge contribution for each basin unit. Applications to assist the design of future construction and hydraulic works could also be envisaged.

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CONCEPTUALIZATION OF GROUNDWATER FLOW IN THE EDWARDS AQUIFER THROUGH THE KNIPPA GAP HYDROGEOLOGIC CONSTRICTION, UVALDE COUNTY, TEXAS

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Abstract

The Balcones Fault Zone Edwards aquifer (Edwards aquifer) is one of the major regional karst aquifers in the United States, with an average withdrawal of 950 million liters per day (L/d). This study focuses on the connection between the Uvalde pool and the San Antonio pool of the Edwards aquifer, west of the San Antonio metropolitan area in Uvalde County, Texas. This area is known as the Knippa Gap and is located north of the community of Knippa. The Knippa Gap is a major zone controlling the flow from the Uvalde pool to the San Antonio pool. The San Antonio pool is the primary source of water for the greater San Antonio water supply. The Knippa Gap is a restriction where the aquifer narrows to a width estimated to be approximately 4 km, is bounded by northeast trending faults of the Balcones Fault Zone on the north, and uplift from the Uvalde salient and igneous intrusive plugs to the south. (Green et al., 2006). The hydrogeology in the Knippa Gap has been a topic of major interest among researchers in this area for numerous years, yet the exact location, nature of boundaries, and karst hydrogeology are not well defined, and the flow through this area is in need of refinement to improve the aquifer water balance.

This study integrates recent research by other scientists with field studies conducted during the summer of 2012 as part of an M.S. thesis. This paper is limited to a discussion of the water quality as it relates to the southern flow boundary of the Knippa Gap near the Devils River Trend of the Uvalde salient. Waterquality data constrain a revised conceptual model of the flow and karstification in this critical area of recharge to the San Antonio pool, and provide specific lateral boundaries and vertical karstification zones which are being tested in the more comprehensive M.S. thesis. Although current interpretations are tentative, it appears this conceptual model will be readily convertible into a digital model that can test hypotheses relating a much broader suite of calibration data, including water levels, water budgets, and spring discharges.

Introduction

The Edwards aquifer, located in south-central Texas (Figure 1), is one of the most prolific artesian aquifers in the world, providing more than 950 million liters of water to more than 2 million people on an average day. In addition, this aquifer is home to more than 40 aquatic subterranean species, several of which are endangered, and one that is threatened (http://www.edwardsaquifer. org/). The Edwards aquifer provides most of the agricultural, industrial, recreational, and domestic water needs throughout its area of occurrence in west-central Texas (Welden and Reeves, 1962; Hamilton et al., 2012).

The artesian zone (confined) of the Edwards aquifer typically occurs at depths ranging from 150 to 300 m with some depths extending up to 1,000 m. The north–south extent of the aquifer ranges between 10 to 60 kilometers, and the east- west is approximately 240 kilometers (Figure 1). Recharge to the Edwards aquifer occurs from the capture of surface water originating from the contributing zone (allogenic recharge), direct precipitation on the recharge zone (autogenic recharge), and inter-formational flow from adjoining formations, both above and below the Edwards Limestone. Discharge in the Edwards aquifer most often occurs by spring flow, pumping, and interformational flow to down -gradient aquifers (Green et al., 2012).

Regionally, the structure of the aquifer is exceedingly complex, owing to the extensive faulting associated with the Balcones Fault Zone. The faulting in the Balcones Fault Zone is primarily *en echelon* normal faulting that is northeast-southwest trending, and is predominantly down to the southeast (Clark, 2003; Barker and Ardis, 1996; Hovorka et al.,2004). The Balcones Fault Zone is


Figure 1. Location of the major hydrogeologic zones of the Edwards aquifer in south-central Texas, by county. The study area of this project is the Knippa Gap in Uvalde County, shown in purple between the towns of Uvalde and Sabinal on the map [Modified from Edwards Aquifer Authority webpage].

thought to delineate the northwestern boundary of the Knippa Gap as a series of faults that have been plugged by low-permeability, fine-grained sediments, and therefore act as no-flow boundaries (Maclay and Land, 1988). South and east of the Knippa Gap, major regional tectonic activity occurred, which includes igneous intrusions and uplift. This event bowed the overlying sediments, including the Edwards Group, uplifting the formations to much shallower depths (Mosher et al., 2006), and resulted in the structural feature known as the Uvalde salient of the Devils River Trend. This feature dips into the Maverick Basin toward the southwest (Figure 2).

Lithologically, the Edwards aquifer in the area of the San Antonio pool comprises as many as 8 members and formations of the Edwards Group, predominantly carbonates and evaporates that were deposited in the latter part of the Early Cretaceous period (Clark, 2003; Hvorka et al., 2004). A pool within an aquifer is a region surrounded by low-permeability zones that restrict dynamic flow out of the region. Most water escapes from the pool by overflowing at low points, such as the Knippa Gap, and springs along the Leona River (Green et al., 2006). In this area of transition in the Knippa Gap, that number decreases from 8 to 3 formations in the Maverick Basin, or 1 formation in the Devils River Trend of the Uvalde salient Figure 3 (Green et al., 2009).

Since deposition, rocks of the Edwards Group have experienced a complex history, including aerial to subaerial exposure, burial (middle Cretaceous), faulting uplift, erosion, and intense karstification (Rose, 1973). In the catchment area of the aquifer (Figure 1), dominant karst processes are epigenic. This means dissolution is produced primarily by descending recharge and horizontal groundwater movement.

However, based on the cave structure and morphological forms such as vertical shafts, scallops,



Figure 2. Location of the Devils River Trend, Maverick Basin, Uvalde Salient and the San Marcos Platform [Adapted from Green et al., 2006].

and cupulas, many researchers conclude that hypogenic speleogenesis (deep regional upward flow) has played an important role in the karst development of the Edwards aquifer (Klimchouk, 2007). Regional flow systems in the Edwards aquifer resurge as large springs where groundwater is returned to the surface from depth. Permeability derived by this upward water flow plays an integral part in the aquifer as well as hydrocarbon storage within the rock unit (Schindel et al., 2008).

Hydrogeologically, the Edwards aquifer is separated into three regional zones, the recharge zone, the contributing zone, and the artesian zone (Figure 1). The contributing zone, identified as the drainage area on Figure 1, captures infiltrated precipitation and allows runoff into streams or infiltration to the water table aquifer to occur. This zone is also where contamination of the aquifer is most likely to occur, primarily as a result of shallow water tables, intense karstification, and little to no soil cover. The recharge zone is dominated by vertical faulting of the Balcones Fault Zone, and is the part of the aquifer where major recharge makes its way to the artesian zone. Entryways are predominantly faults of the Balcones fault zone, and major inputs are point and line sources where streams and rivers cut across this zone of faulting. The artesian zone is the southern and easternmost part of the aquifer where water is confined. The confining layers for the Edwards are the Glen Rose Formation below and the Del Rio Clay above (Figure 3).



Figure 3. Stratigraphic column from southwest to northeast across Uvalde County in the study area, Knippa Gap. Karstified focused flow zones of the Edwards are shown in blue [Modified from Green, 2009].

Problem Statement

The Edwards aquifer has been intensively studied, but many important questions remain unanswered. One major question deals with groundwater flow through the Uvalde County area (Figure 1) known as the Knippa Gap (Figure 4). This part of the Edwards aquifer represents an overflow zone approximately 4 km wide bounded by northeast trending faults of the Balcones Fault Zone. Water discharges from the Uvalde Pool on the west into the San Antonio Pool in the east. Southeast of the Knippa Gap uplift was caused by igneous intrusions forming the Uvalde salient structure, resulting in little or no flow and minimal well yields in this part of the aquifer essentially a zone of no flow along the southeastern edge of the Uvalde Pool (Green, 2006). The amount of groundwater flow that discharges through the Knippa Gap is not well constrained, in part because a significant portion of outflow from the Uvalde pool discharges to the south through subcrops to the Leona gravels. More refined flow estimates, along with a better understanding of how the Knippa Gap functions, would greatly refine the water budget for the San Antonio Pool and more accurately determine flow boundaries and budgets for the Uvalde pool.

Objective and Scope

The object of this report is to refine the conceptual model of flow in the Edwards aquifer through a flow constriction in Uvalde County, Texas, known as the Knippa Gap. Discussion here is limited to the factors related to water quality; however, this paper is only a small part of a much broader M.S. study of the karst hydrogeology of the region.

Study Area

The study area is shown in the shaded region of Figure 4. An expanded but secondary area of interest surrounds the main study area, encompassing contiguous portions of the integrated Edwards aquifer flow system. The Edwards aquifer in Uvalde County is predominantly composed of Lower Cretaceous carbonate (dolomitic limestone) of the Devils River Formation within the Devils River trend in the northeast, transitioning into the West Nueces, McKnight, and Salmon Peak Formations in the Maverick Basin in the southwest.

These carbonate rocks were formed in evolving environments that ranged across a variety of tectonic and depositional conditions. The Devils River Trend was an open, shallow-marine environment of high current energy, whereas the West Nueces, McKnight, and Salmon Peak Formations were restricted to open marine, deep-basinal environments (see Rose, 1973). The upper units of the Devils River Trend along with the upper unit of the Salmon Peak Formation are the most prolific water bearing units in the study area.

Throughout the study area there are numerous Upper Cretaceous or Lower Tertiary igneous rocks that intrude through the stratigraphic units composing the Edwards aquifer (Clark, 2003). Uvalde County contains multiple minor groundwater resources from a thick sequence of sedimentary rocks. The Edwards is by far the most significant of these aquifers, spanning the central portion of the county from west to east. The Buda, Austin Chalk, gravels of the Leona River, and the Trinity aquifers are the major secondary aquifers that are present in Uvalde County. (Green, 2009) Several noteworthy structural features have been studied throughout Uvalde County, such as the Uvalde salient (resulting from crustal uplift, faulting, and igneous activity that elevates the Edwards aquifer to the surface across the central region of the county), and the Balcones fault zone (a tensional structure area aligned southwest to northeast across the study area). Preliminary interpretation of the Knippa Gap indicates that it is a structural feature that acts as a barrier, separating the Uvalde pool from the San Antonio pool under Medina, Bexar, and Comal Counties. It is described as being a narrow opening in an extensive system of barrier faults. (McClay and Land, 1988) Although 2.4 x 1011 liters (200,000 acrefeet) are estimated to flow through the Knippa Gap annually, the constriction causes water levels to build up in the Uvalde pool. Green et al. (2006; 2009a; 2009b) conclude that the Uvalde salient has several prominent structural high points that constrict the groundwater flow through "topographic saddles" between the high points. They also note the large amounts of recharge from the Frio and Dry Frio Rivers that are contributing to the groundwater flow in the region, and conclude that the Knippa Gap flow constriction and the incoming recharge cause a damming affect for the groundwater up-gradient and west of the gap (Green et al., 2006). Water use in the east is significant, owing to close proximity to the cities of San Antonio, New Braunfels, and San Marcos. Recharge of the aquifer is greatly impacted by periodic droughts, and the flow of the recharge from west to east is significantly constricted in the area of Knippa Gap.

Methods and Approach

The hydrogeology and eleven wells described herein (Table 1, Figures 4, 5, and 7) were sampled for field parameters and major-element geochemistry to evaluate areal distribution of water quality and to redefine flow boundaries in the conceptual model.

The conceptual model (Figure 7) incorporates samples contiguous to the study area, displaying the major ion compositions of these samples. These data allow visualization of geochemically related waters, and the determination of flow paths. These data also facilitate an understanding of the geochemical processes acting in the flow system, and help to characterize evolution of water type in the aquifer. These should

QW Site	Well ID	Date	TDS	Temp °C	Cond	рН	Ca ⁺²	Mg ⁺²	Na ⁺	K+	ALK	Cŀ	SO ₄ ⁻²
1	YP-69-43- 606	6/18/2012	237	23.5	481	7.20	82.1	10.4	10.8	1.07	203	19.9	12.3
2	6943919	6/18/2012	1210	26.6	1605	6.98	277	27	28.1	2.91	169	72.9	630
3	69433JY	6/18/2012	260	23.6	471	7.25	79.9	10.3	9.93	0.974	188	20.6	11
4	6943903	6/18/2012	340	23.9	477	7.49	86.8	9.28	11.1	1.1	203	20.2	11.7
5	6943701- W101-561	6/18/2012	877	24.7	1274	7.24	168	21.9	77.8	5.62	241	158	196
6	6943803	6/18/2012	353	24	502	7.27	85.3	8.33	11.7	1.03	206	23.8	12
7	69439MB W101-594	6/19/2012	376	24.7	701	7.16	93.1	17.8	25.6	2.36	200	55.5	55.9
8	69436JS	6/19/2012	238	25.1	428	7.36	63.9	13	6.9	0.097	179	14.1	11.5
9	6942606	6/19/2012	303	23.6	502	7.21	80.3	8.22	11.7	0.973	199	33.5	10.6
10	69-50-3BR	6/19/2012	344	23.2	601	7.37	88.8	9.19	21.3	0.962	212	42.8	18
11	69-43-103	6/19/2012	365	23.8	448	7.19	93.2	9.57	24	1.09	215	51.1	19.2

Table 1. Selected water quality and dissolved constituents in water from wells in the study area. QW Site number is referenced to Figure 4. Chemical parameters are in mg/L. [QW, water quality; TDS, total dissolved solids, in mg/L; Cond, specific conductance, in μ S/cm]

not be used alone to delineate the gap, but they are a good conceptual start to test alternative hypotheses. Considering the complex faulting in the immediate area, they are consistent with a structural basis for constructing the boundaries of the Knippa Gap.

Results

Table 1 shows the water quality and dissolved constituents in water from wells located within the study area. The Well ID in Table1 is referenced to Figure 5, and the QW Sites to Figure 7. Figure 5 includes 2 sample sites (QW site 69439JA, and 6950310) that were excluded from Table 1 owing to cation/anion imbalances outside the range of 5% error.

Table1 and Figures 6 and 7 indicate the presence of high sulfate and high chloride waters with higher

specific conductance (701 to 1605 mS/cm) and higher temperatures (26.6 to 24.7 °C) that occur in wells within the Uvalde salient (QW Sites 2, 5, 7). Waters west (QW Sites 4, 6, 8, 9, 10, and 11) and east (QW Sites 3 and 1) of the salient are calcium-magnesium bicarbonate waters with lower dissolved solids (428 to 601 μ S/cm) and slightly lower temperatures (23.5 to 25.1 °C). QW Site 8 represents the least mineralized of all wells sampled, not only in terms of specific conductance, but also in terms of the lowest concentrations of dissolved chloride and dissolved sulfate. Various degrees of mixing of waters from different sources are present in these latter wells, reflecting variations in lithologies along the flow path.

Conclusions

The conceptual model (Figure 7) allows visualization of water type and major flow directions that are



Figure 4. Location of key components of the Knippa Gap, the expanded study area, and other relevant hydrogeologic features in Uvalde County [Modified from Green, 2009].



Figure 5. Geology of the Edwards aquifer in the study area, including areal geology, faulting associated with the Balcones fault zone (red lines), exposures of igneous intrusives associated with the Devils River Trend of the Uvalde salient (in red), and sampling sites of wells used to measure water levels and collect groundwater samples. The numbers refer to the sampled wells discussed in Table 1. [Map modified from multiple sources, including Clark, 2003; Green, 2006, and personal communications with Vic Hilderbran, Uvalde County Water Conservation District and Rob Esquilin, Edwards Aquifer Authority].

superimposed on Figure 5, (which includes the Balcones Fault Zone and outcrops of intrusive igneous rocks that roughly define the Uvalde salient), defines likely flow boundaries for the Knippa Gap. Piper (Figure 6) and Stiff (Figure 7) diagrams from sites designated as Knippa Gap wells plot within the carbonate dissolution field, and have specific conductance values that are generally in the range of 400-500 mS/cm, and temperatures in the range of 23 to 24 °C. QW Site 8, the least mineralized well sampled, is the only exception to the temperature range listed, with a value of 25 °C. In addition to flow boundaries and flow directions, Figure 7 also indicates the approximate location of the subsurface overflow from the Uvalde Pool to the Leona gravels.

Stiff diagrams for QW Site 2 is thought to lie near the bad water line, an arbitrary line defined by total dissolved solids greater than 1,000 mg/l and defining the southern boundary the freshwater portions of the Edwards aquifer. Increased mineralization is a result in increased contact with gypsum and has more limited development of



Figure 6. Piper diagram of groundwater in the study area showing water quality types ranging from waters within the Knippa Gap (within black circle) to waters derived from mixing of high sulfate and chloride waters associated with residual evaporites in less dynamic flow zones (see wells 2, 5, and 7 in Table 1). secondary permeability than the freshwater portions of the aquifer. These factors result in greater salinity levels and distinctive Stiff diagrams. The conceptual model (Figure 7) shows that (OW) sites 5 and 7 plot along a mixing line of meteoric water and down gradient water similar in chemical composition to well 2. As indicated by the curved blue lines on the model, these QW sites have mixing components that are inconsistent with focused flow through the Knippa Gap, and do not lie in the main flow zone of the Edwards aquifer. The high specific-conductance waters with higher concentrations of chloride and sulfate cannot be rectified with rapid groundwater flow zones and major karst development. Most of the wells with these attributes overlie the Uvalde salient, and because of the structural uplift, the aquifers are closer to surface-water inputs. It is speculated that this proximity may contribute to slightly higher temperatures although this needs to be investigated further. Well yields in this area are also consistent with much less flow (and dissolution of the highly soluble evaporates) through this part of the aquifer. Well 11 is an exception to this, but inasmuch as it lies on the boundary of this study and its explanation at this point is not obvious.

Data from the remaining QW sites have Stiff diagrams representing the fresh fast-flow zones with dissolution as the main geochemical process. These QW sites plot within the carbonate dissolution field of the Piper diagram (Figure 6) as well, and have calculated TDS values ranging from 228 mg/L to 353 mg/L further supporting the evidence for the constricted flow path of the Knippa Gap.

Future Work

In addition to the geochemical analysis discussed in this paper, the larger M.S. study will incorporate the compilation of a complete table of wells, geophysical wireline logs, water-quality analyses, water-levels, well yields, driller's records, tracing studies, and aquifer tests within the study area. The completed table of wells represents sites with multiple names and aliases, and will aid in future investigations for cross-referencing data, most of which are not in accessible digital format. The table will involve historic published well data, and unpublished records from drillers, water managers, and hydrogeologists in the area, and will be supplemented by field inventories of wells which will be conducted during the summer of 2013.



Figure 7. Conceptual model of the Edwards aquifer in the study area, showing Stiff diagrams that reflect major element concentrations dissolved in groundwater (in green), approximate locations of boundaries of flow through the Knippa Gap (curved blue lines), major flow directions through the Knippa Gap constriction (blue arrows), subsurface overflow from the Uvalde Pool to the Leona gravels (black arrow), and exposures of igneous intrusives associated with the Devils River Trend of the Uvalde salient (in red). Sampling sites of wells for which chemical analyses are reported are shown by black dots; the numbers refer to the sampled wells discussed in Table 1.

A synoptic potentiometric map of the study area will also be assembled. This map will utilize waterlevel data collected from the field during low-stage conditions during the summer of 2012. This effort will incorporate historical water-level data collected by the Edwards Aquifer Authority (EAA), and the results will be used to evaluate potential boundaries, assess variability of aquifer hydraulic properties, and indicate flow directions.

A hydrostratigraphic analysis, incorporating a conceptual model of the Knippa Gap based on drilling and wireline logs, will be helpful to redefine placement of faults (flow boundaries), aid in determining physical constraints and boundaries within the Knippa Gap and improve characterization of the depth of karstification within the study area.

A final assessment in this study should be a tracer test in the study area to evaluate groundwater flow velocities and directionality. A proposed injection site is a sinkhole located very near the southern flow boundary associated with the Uvalde salient (star on Figure 5). Tracer testing is one of the most effective ways of quantifying groundwater movement in karst aquifers, and will provide empirical data that will aid in the determination of the groundwater flowpaths, velocities, dispersion, storage, and dilution components for this region (Schindel et al., 2008).

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DELINEATING SOURCE AREAS TO CAVE DRIPS AND CAVE STREAMS IN AUSTIN, TEXAS, USA

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Abstract

Delineating the source area of cave drips and streams (subsurface infiltration catchment area) is important for maintaining high-quality water sources critical for healthy cave ecosystems. In order to focus protection for cave ecosystems, particularly those containing federally listed species, it is necessary to accurately delineate the potential contributing infiltration area with high confidence.

Various methods are used in conjunction to delineate subsurface infiltration catchment areas in four Balcones Escarpment sites (Buttercup Creek, Barker Ranch #1 Cave, McNeil Drive, and Davis Lane). The methods consists of 1) observation and flow measurement of drips, speleothems, pools, and streams under wet and dry conditions to characterize drips as discrete or seepage, 2) cave mapping surveys to determine spatial relations and elevation of drips, speleothems, pools and streams, 3) hydrostratigraphic characterization (dip of beds, faulting, and the rock tendency to perch vadose groundwater downward at a minimum hydraulic gradient), 4) waterquality characterization and comparison with potential sources and 5) dye and chemical tracing. Steps 4 and 5 provide the most direct delineation of source areas based on the detection (or non-detection) of tracers and injection locations. Not all of the methods were applied at all four study sites and some catchment areas are so large that they were not completely delineated without additional investigation.

Mapping the highest elevation of a drip source in a cave limits the surface extent of any infiltration source area. A non-persistent, seepage drip is more likely to originate from soil-moisture drainage close to the cave footprint. Direct tracing of vadose groundwater illuminates the influence played by dip and lower permeable hydrostratigraphic units in perching groundwater and directing vadose flows long distances to drips and cave streams. Injected tracers measured minimum hydraulic gradients of 0.4 to 3% across lower permeable hydrostratigraphic units and minimum hydraulic gradients of 12% across higher permeable units. The updip outcrop of the top of a perching lower permeable unit, as well as caves that breach the lower permeable unit, may be used to define the extent of a subsurface catchment area. Through deeper investigation of the caves using various methods together, the mapped subsurface catchment areas are refined to a focused source area. Where insufficient data are available to constrain the boundaries, the subsurface catchment area should always be conservatively overestimated.

Introduction

Rare cave species in Travis County, Texas, are protected by a federal permit awarded to the City of Austin and Travis County (USFW, 1996). Sixty-two caves were identified that if sufficiently protected could provide suitable habitat for listed endangered karst species and ensure that other rare species of concern would not require federal listing as endangered in the future. Cave species require clean and sufficient water for sustenance, so hydrogeological studies are conducted to identify water catchments that provide direct runoff to the cave entrance (surface catchment area) as well as the overlying area that supports cave drips and cave streams (subsurface catchment area) through subsurface infiltration. Since the delineation of surface catchments is considerable more direct and is described elsewhere (Hauwert, 2009), this paper pertains only to delineation of subsurface catchment areas, except where surface catchments contribute to areas of subsurface infiltration that supply the studied drips.

Basic methodology for delineating source areas are described by Quinlan et al (1995) and Goldscheider and Drew (2007). For delineating subsurface catchment areas for cave drips and cave streams of the Edwards Aquifer, it is important to have an understanding of recharge and storage through the soils and epikarst. In the 1980s, studies were conducted that examined recharge within the Barton Springs Segment, how groundwater moves through the aquifer. Using a water budget approach based on stream gauging and rainfall measurements. Assuming that all recharge in Barton Creek channel of the recharge zone discharges from Barton Springs, it was calculated that 85% of rainfall was lost to evapotransporation, 5% of rainfall recharged within the major creek channels, and only 0.89% of rainfall infiltrated the ground and recharged the aquifer within the intervening areas between the major creek channels (Woodruff, 1984). However, the 1980s water balance was invalidated in 1996, when direct groundwater tracing and water level mapping revealed that the entire portion of Barton Creek where flow loss was measured and attributed to recharge is not actually within the groundwater basin contributing to Barton Springs (Hauwert, 2004; Hauwert, 2009). That error alone comprised 28% of total recharge to Barton Springs in the water budget, and explains why the Edwards Aquifer was erroneously attributed a recharge value similar to those measured over the Eagle Ford Shale (Hauwert, 2009). Hydrogeologic studies commonly fail when based on an incomplete understanding of groundwater source areas, as well as often erroneous assumptions are that only major creeks supply significant recharge, that upland soils do not allow infiltration into the underlying bedrock, that groundwater flow is slow, and that groundwater transport generally has high dispersion and attenuation (Hauwert, 2009; Hauwert, 2012a).

Karst aquifers typically show recharge values of 20 to 60% of rainfall because of naturally efficient recharge structures (Hauwert, 2009). Initial site-specific measurements from Central Texas used climate towers in Uvalde County discovered that of measured rainfall, 65% was lost to evapotranspiration, 5% to runoff, and 30% to recharge (Dugas et al, 1998). Climate towers combined with flumes provided a more direct measurement of recharge since they quantify roughly 70% of the rainfall budget as opposed to roughly 5 to 15% of the rainfall budget measured through streamflow loss. A 1.4-year site-scaled water balance within the Barton Springs Segment used an eddy covariance tower, rain gauges, and flumes to measure rainfall components as 68% evapotranspiration, 3% runoff that entered the drain of an internal drainage basin, and the remaining 29% recharged the aquifer from upland slopes. Using gauging station data distinguished by traced groundwater divides, about 63% of rainfall was estimated to be lost as evapotranspiration, 22% recharged over the Edwards Aquifer recharge zone, and 15% discharged into major creeks and ran off downstream of the recharge zone (Hauwert, 2013).

The general influences of geology on cave development and vadose flow are described by White (1988); Palmer (2007), and Goldscheider and Drew (2007). The degree to which stratigraphy influences groundwater flow varies with permeability contrast and aquiclude thickness, as well as the degree of faulting (Goldscheider, 2005). Veni (1992) summarized the effects of geology on cave development described by White (1988) and Ford and Williams (1989) including: vertical cave shafts generally develop above the water table and are associated with beds of lower permeability or lower solubility; horizontal cave passages develop in high permeability beds; caves typically become impassible at common lower permeable/lower solubility horizons or due to sediment fill; and springs discharge near horizons of permeability contrast and their discharge is proportional to the size of its catchment area. Rose (1972), Maclay and Small (1986), and Small et al. (1996) described the general characteristics of the hydrostratigraphic members of the Edwards Aquifer (Table 1). Hauwert (2009) described in greater detail how the hydrostratigraphic properties of the Edwards Aquifer influence cave development and groundwater flow within the Barton Springs Segment of the Edwards Aquifer.

Geologic structure strongly influences vadose flow in karst areas. In unconfined areas of karst aquifers, vadose flows tend to flow in a downdip direction where stratigraphic dip is present (Palmer, 1977; Ginsberg and Palmer, 2002; Veni, 1992). Downdropped faults often create a hydraulic gradient within the unconfined portion of Edwards Aquifer that simulates the effects of stratigraphic dip, even where local dip is absent (Hauwert, 2009). Rock-strata within the Edwards Aquifer may also dip nearly parallel to scissor fault directions within ramp structures (Collins, 1995).

Methodology

The subsurface catchment area for a cave drip or cave stream can be constrained within a defined area simply by mapping the surface extent of any connected

Table 1. Hydrostratigraphic units of the study areas. Modified from Small et al. (1996) and Hauwert (2009). While the Basal Nodular Member appears equivalent to the Comanche Peak and Walnut Formations of North Austin, it has not been formally correlated.

Hydrogeologic subdivision	Group	Formation	Member	Full Thickness (m)	Lithology	General Hydrogeologic Properties		
í	1	Del Rio	-	15 - 18	Clay	Low permeability clay		
1	Washita	Georgetown	1 1	12 - 18	Nodular fossilferous limestone	Low permeability overall with local vertical fissure development		
		Person	Leached and Collapsed undivided	0 - 21	Wackestone and grainstone with mudstone matrix	High permeability with extensive horizontal and vertical cave deveopment		
2		L	Regional Dense	4.5 - 10	Well-sorted fissile mudstone	Local aquitard frequently breached with vertical fissures and shafts.		
Edwards Aquife	Edwards	Kainer	Grainstone	14 - 18	Massive, resistant, miliolid/ chondrodont grainstone	Highly variable moderate to high permeability. Tigh corkscrew cave passages and enlarged bedding plane rooms. Commonly serves as competent roof over Kirschberg Mbr		
			Kirschberg	12-23	Crystalline limestone and pulverulite	High permeability with extensive cave development associated with pulverulitic beds. Extensive dissolution and breakdown.		
			Dolomitic 9 - 43 Highly bedded with sandy or dolomitic matrix		Highly bedded with sandy or dolomitic matrix	Moderate fissure-dominated permeability with significant cave development		
			Basal Nodular*	16 - 32	Fossilferous, nodular limestone	Low permeability breached by vertical pits and fissures. Produces many minor springs.		
Upper Trinity Aquifer	Trinity	Upper Glen Rose		100 - 150	Alternating massive limestone, dolomite and marl layers	Overall low permeability with conduit network supporting abundant springs/wells. Hydraulic connection with Edwards Aquifer and cave development documented in some areas.		

land surface elevation than the cave. This approach is appealing because it requires very little data from the cave other than the total cave depth and surface topography, and includes the entire actual source area to cave drips with high confidence. However, subsurface catchment areas defined based solely on the cave depth projected topographically on the surface typically extend for long distances from the cave, greatly overestimating the actual subsurface catchment area. The purpose of deeper hydrogeological study of the cave is to allow the investigator to limit the size of the defined subsurface catchment area, but include all of the source area for subsurface infiltration to the cave with high confidence. The methods utilized in studies to map subsurface catchment areas involve a combination of cave surveys, geological framework mapping, water-quality sampling, and introduced tracers. Note that in each of the study areas, emphasis is placed on some of the methods that were most useful for the specific location.

Cave Surveys

The depth and lateral extent of the cave constrains the subsurface catchment area. The lateral extent of the cave beneath the ground is known as the cave footprint. Without the completion of additional study beyond mapping the cave, the lowest elevation of the cave can be used to eliminate areas of lower elevation as being outside the subsurface catchment area.

The cave is mapped from an entrance survey point using station-to-station measurement of distance, azimuth, and inclination as described by Dasher (1994), Jeannin et al (2007), and Ochel and Shade (2013). Distance is measured using a nylon tape or Bosch laser survey. Azimuth is measured using either a Brunton and/or Suunto tandem compass. Magnetic declination was set on the compasses and verified by recording test azimuths to surface objects over 30 m away and locating the start and finish with a Trimble XT. Inclination was measured

with a Tandem inclinometer and Brunton compass inclinometer. Where possible, forward and back shots were taken between each station and any discrepancies were resolved through repeat measurement.

Existing cave maps provide valuable information but generally do not provide sufficient information alone. Drips in the caves were rarely mapped on existing cave maps for the study area. Most caves referenced in this report were resurveyed even though existing maps were available. The difference between two cave surveys was used as a fair indication of where the cave footprint lies. Cave radio location was used on longer caves to locate the surface position and depth of several stations within the cave. The elevation of the cave drip is derived from the cave survey and/or cave radio location. As general criteria, the subsurface catchment area should extend at least100 m beyond the cave footprint.

Characterization of drips and cave streams

If the highest point of origin of a cave drip or cave stream can be established, then that drip horizon, rather than the bottom of the cave, can be used to delineate a source area. Note that drips within the cave may originate from different sources unless associated by physically following the flow from one point to another, analyzing water-quality similarity, or tracing the flows. A general summary of cave drip characterization is provided by Jeannin et al (2007).

Cave drips are characterized as discrete or seepage. A discrete drip or cave stream may flow from an open aperture/conduit/cave. Its discharge is focused in one or a few locations. A seepage drip has discharge distributed from many formations across a ceiling. The persistence of a drip or cave stream is characterized at various times under wet and dry conditions, particularly during or shortly after an intense storm where the soils are saturated. Methods used to quantify cave drip rates include using a graduated plastic cylinder to measure the drip volume over a measured time interval. Plastic Rainwise tipping buckets with Onset Microstation data loggers are used on some drips to measure drip rates continuously, allowing changes in drip rate to be correlated with rain event cycles or anthropogenic sources such as swimming pool draining or utility line leak. In a cave room with widely dispersed cave drips, one cave drip rate volume is measured to estimate drip volume per drip, and other drips in the room are

quantified by quietly counting drips over a two-minute interval, and later quantifying the drip rate of the entire room. Cave streams are typically measured by filling a waterproof cave pack of measured volume by capturing the entire flow at a pour-off point.

Speleothem types may be used to characterize sources. Stalactite, stalagmite, column, flowstone travertines, and bacon rinds may be associated with discrete drips. Soda straws are typically associated with seepage drips. Popcorn is typically associated with seepage flow through pores, although it is possible that a discrete source is transmitted through a porous media, such as a pulverulite.

When accessing caves for studies it is recommended and possibly required by local permitting to have trained cave specialists and cave biologists. A cave specialist can ensure the cave is entered safely and determine where specialized techniques such as negotiating vertical techniques or tight crawls are required. Cave biologists frequently accompanied trips into caves during this study to minimize impacts to the cave ecosystem.

Hydrostratigraphic Mapping and Characterization

The general properties of the rocks and the geological framework, such as rock dip and fracturing of the rocks, can be used to understand the basis for groundwater flow horizontally and vertically. Detailed mapping of the surface and subsurface geology is an important step for delineating subsurface catchments.

Hydraulic gradient

One criterion for delineating subsurface catchment areas is based on the properties of the rocks between the surface and cave drip. Using tracing and direct observation of cave passages through various hydrostratigraphic units, the vertical movement of water can be quantified in terms of a minimum vertical hydraulic gradient. This criterion can be applied only to sites where the hydrostratigraphic units are accurately mapped on the surface and subsurface.

In highly permeable and soluble rocks, water will tend to descend relatively steeply even where fractures, faults and fissures are not present. In low permeable rocks, groundwater flow is more likely to "stair step" downward, flowing horizontally along stratigraphic dip and periodically descending vertically along fissures and shafts. In low-permeable limestones and dolomites dissolution is strongly enhanced along fractures, perching above less-permeable beds and descending down fissures and shafts.

Within the highest permeability hydrostratigraphic units, such as the Leached and Collapsed Members, Kirschberg, and Grainstone Members, while cave passages may extend horizontally through these units, the passages were formed in the phreatic zone, and under unsaturated zone conditions small flows have not been observed to extend far horizontally before descending (Hauwert, 2009). Note that where cave passages in overlying permeable units overlie relatively lower permeability beds, such as cave passages within the Leached and Collapsed Member over the Regional Dense Member, it is the underlying low-permeability bed that controls the hydraulic gradient. Lower permeability units within the Basal Nodular Member/Walnut Formation, Regional Dense Member, and the Dolomitic Member tend to perch groundwater for some distance until breached by shaft. So the lower permeability units have both very low and very high vertical gradients of vadose groundwater flow.

The property of hydrostratigraphic units to perch groundwater can be quantified as minimum hydraulic gradient that is the distance that a tracer travels divided by vertical depth above or through that unit. Based on the mapped hydrostratigraphic units between the surface and cave discharge, the mapped subsurface catchment area should extend at least beyond the minimum hydraulic gradient measured for those rock units unless other criteria exist, such as direct tracing used to indicate a higher hydraulic gradient and smaller source area. All units potentially have a high hydraulic gradient (vertical), such as where shafts or fissures are present. Definition of the minimum hydraulic gradient from a drip to the surface provides a criterion to limit the lateral extent of potential source area.

The minimum hydraulic gradient is tested on a siteby-site basis through the various hydrostratigraphic members through which the groundwater travels. For the sites traced, the hydrostratigraphic units are mapped across the surface, in caves, in logged wells, and from cores to define the subsurface extent between the surface and entire cave depth. It is possible that a lower gradient exists across a hydrostratigraphic unit than we tested, so this criteria should be used with caution to limit the size of the subsurface catchment area, particularly in the updip direction of a cave drip, where a persistent discrete drip suggests a larger source area, and obviously where a traced flow path indicates a lower hydraulic gradient.

Geologic Framework: Stratigraphic Dip and Faulting

In order to examine geological controls of vadose groundwater flow, the geological framework is mapped, including stratigraphic dip and faults. In areas between mapped faults, the location and elevation of distinctive marker beds are located using global positioning systems within 1 m (3 ft) horizontal and vertical accuracy. Using a three-point problem solution, the maximum dip direction and maximum dip magnitude are calculated (Compton, 1962). The stratigraphic dip directly measured at the site scale, and the measured local dips rarely coincided with regional dip reported in the literature. Single outcrop and cave measurement of small-scale dip seemed to vary more with local collapse and generally were not representative of overall dip within fault blocks.

The subsurface catchment area typically extends in the stratigraphic updip direction from the cave discharge. Despite the general rule of downdip vadose flow, exceptions have been observed where vadose flow essentially ignores stratigraphic dip and follows faulted preferential flow routes directly to a local spring site, sometimes perpendicular to down dip and down faulting direction (Hauwert, 2009). Faults are generally poorly exposed in the Austin area and are most commonly mapped using abrupt change in surface hydrostratigraphic units. Detailed site geology mapping is generally necessary to distinguish elevation declines in marker beds due to faulting, stratigraphic dips or other geologic structures.

If a lower permeable hydrostratigraphic unit is discovered to have a defining influence on perching groundwater flow, then the extent of updip outcrop of the top of the low-permeable unit was generally used for defining the extent of subsurface source area, even where minimum hydraulic gradient values define smaller subsurface catchment areas.

Other structures that may limit the extent of the subsurface catchment area are caves that breach lower permeable perching units or descend below the drip horizon in the studied cave. These are known as breach structures in this study. In cases where narrow topographic saddles were connected by continuous higher elevation to the cave drip, it was deemed unlikely that a vadose flow path would follow a ridge or perhaps take erratic turns rather than discharge into an adjacent tributary.

Water-Quality Characterization

Water quality similarities help associate drips within the same cave or characterize sources to those cave discharges. Water-quality association is not as direct as tracing, therefore involving more interpretation. Waterquality characterization is necessary where tracing cannot be conducted to associate drips with a source area or where tracer was not recovered at specific discharges. The source water sampling parameters included alkalinity, calcium, carbon, chloride, fluoride, magnesium, potassium, sodium, sulfate, bromide; trace metals: aluminum, arsenic, boron, cadmium, chromium, copper, iron, lead, nickel, strontium, zinc; nutients: nitrate + nitrite, ammonia, phosphorus; and total suspended solids. The samples were filtered and preserved for most parameters. Bacteria samples are collected using both grab and autosamplers. When collected using autosamplers, blank bottles are tested for total coliform and E. coli to test for bottle contamination.

Dye and Chemical Tracing

Dve traces successfully traced groundwater flow paths over 32 km (20 mi) in the Barton Springs Segment (Hauwert, 2009). Because aquifer-wide tracing utilizing sodium fluorescein/uranine, eosine, rhodamine wt, and sulforhodamine b, and phloxine b is nearly continuously being conducted within the Barton Springs Segment, those tracers could not be used in our short vadose tracing. Organic tracers are also notoriously sorbed by organic debris and sediment and are most effective when injected in open apertures. The advantage of organic tracers is that they can be monitored continuously using charcoal receptors for dyes and cotton receptors for optical brightners. For soil tracing we frequently use the optical brightners tinopal and direct yellow 96, as well as the dye pyranine, even though they are not ideally suited for soil tracing, and frequently not recovered alongside simultaneously injected chemical tracers. All analysis for dyes and optical brighteners was conducted by Ozark Underground Laboratory in Protem, Missouri.

Chemical tracers commonly used include potassium bromide (KBr), ammonium carbonate ((NH4), CO₃),

and 10,000 mg/l iron standard solution (Fe). The disadvantage of chemical tracing is that if the sampling intervals selected are too wide, a short breakthrough pulse might be missed and a composite sample may dilute the pulse to the extent that it is undistinguishable. A frequent sampling cycle can also be expensive and labor intensive. Analysis for K, Br, NH₃, alkalinity, and iron are conducted by the Lower Colorado River Authority lab in Austin, Texas. All tracers in this study were flushed using natural rain events except for the Buttercup Creek site, where organic tracers were injected into cave streams.

Where tracers targeted cave species preserves, biological surveys of the caves were conducted by permitted cave biologists to verify that the amount and type of tracer were not visibly affecting the cave ecosystem. The type of tracers and injection amount were similarly considered so as not to create a nuisance or health hazard. At the concentration of tracers in the phreatic zone, the tracers were relatively benign, especially compared to actual contamination sources that have affected or could potentially affect these water supplies. The risk of potential impacts to the species or water supply users can be considered in light of potential impact sources that may be much worse than the tracers used. The information gleaned by direct tracing can help focus long-term protection efforts as opposed to less effective disperse and resource intensive efforts over a large area that may offer limited protection.

Study Sites

Four study sites include Buttercup Creek, Barker Ranch, McNeil, and Goat/Blowing Sink karst preserves (Figure 1.)

Buttercup Creek Study, Northern Segment

In 1997, two organic dyes were injected into cave streams of Marigold Cave and Whitewater Cave by Mike Warton & Associates of Cedar Park, Texas. This study was funded by Lumbermans Investment Corporation and the report submitted to US Fish and Wildlife Service (Hauwert and Warton, 1997). Monitoring was conducted by Nico Hauwert and Mike Warton & Associates using charcoal receptors and grab samples. The caves included horizontal passages and shafts through the Comanche Peak Formation and Walnut Formations that underlie the Edwards Formation in the Northern Segment of the Edwards Aquifer. This study differs from the other three study site examples in that flow from cave streams to



Figure 1. Location of four study sites, Austin, Texas, USA.

surface discharge spring were traced, rather than surfaceto-cave drip or cave stream.

Barker Ranch #1 Cave

Barker Ranch #1 Cave is a relatively shallow upland cave of relatively high topography. One large room adjacent to the entrance has multiple drips that are persistent (Figure 1).

The cave is developed within the Grainstone and Kirschberg Members of the Edwards Group. A soil tracing study funded by the City of Austin Watershed Protection Department in 2007 involved pouring tracers at six surface locations across the site and monitoring Barker Ranch #1 Cave drips for any breakthrough. Natural rain events were used to flush the tracers along with 15 liters of water solvent for powder tracers (Cowan et al., 2007). The chemical tracers used were potassium bromide (KBr), ammonium carbonate ((NH4)₂ CO₃), iron standard (Fe), sodium chloride (NaCl), and potassium iodide (KI). Three traces were repeated to verify results or replace a failed trace. Supplemental organic tracers were used alongside chemical tracers, including dyes sulforhodamine b (SRB) and pyranine, as well as optical

brightener direct yellow 96 (DY96). Even though the drips in Barker Ranch #1 are relatively persistent for months after rain, the onset of drought following the third round of simultaneous tracing eventually led to the drips in Barker Ranch #1 drying for several years, resulting in the end of injections to Barker Ranch #1 Cave.

2009 Study along McNeil Drive

Several caves near McNeil Drive contain listed endangered species, including McNeil Bat Cave, Weldon Cave, No Rent Cave, and Fossil Garden Cave. The study involved surface mapping of the area, examining local quarries and drilling bores and geotechnical borings to gain subsurface geology data and measure local dip (Hauwert, 2010). Three of the four caves were remapped relative to professionally surveyed surface monuments at the cave entrance. The drips were observed under varying climatic conditions. No tracers were injected for this study.

2012 Study along Davis Lane

A study of Goat Cave, Maple Run Cave, and Blowing Sink Cave was conducted by Nico Hauwert of City of Austin and Brian Cowan and support staff from Zara Environmental in 2012, funded in part by City of Austin Public Works Department and by a spill simulation Capital Improvement Project by the Watershed Protection Department. The study involved surface and subsurface geological mapping, cave and drip mapping, water-quality sampling of surface drips and runoff, and tracer injections at various surface locations. Chemical tracers (potassium bromide, ammonium carbonate, and iron) were used, along with optical brightners tinopal, direct yellow 96, and pyranine. A cave radio survey of Maple Run Cave was conducted.

Results

In the three cave drip studies, the cave drips were found to be localized in specific areas and not distributed throughout the cave. Both seepage and discrete drips were encountered. The localization of drips within the caves suggests that epikarst and vadose flows converge along common flowpaths rather than diffusely flowing through small pores within the entire rock column.

1997 Buttercup Creek

The two tracers injected, fluorescein and RWT, moved 5 km (3 mi) southwest, apparently along a mapped fault and discharged from Blizzard Springs, which discharged on the west (opposite) side of Cypress Creek. Blizzard

Springs discharges from the base of a bluff, about 5 m (15 ft) below the contact of the Walnut Formation in the upper Glen Rose Formation. The Walnut Formation is generally less soluble than the overlying Edwards Formation, but hosts extensive cave development along fissures. Although local mapping of stratigraphic dip was not included in this study, mapping elevation changes several kilometers south have shown a relatively consistent eastward decline in the contact of the Edwards and Walnut formations. Since the tracers were injected within cave streams that likely have large contributing source areas, only a portion of the subsurface catchment area was defined.

2007 Barker Ranch #1 Cave

Four of the six injection sites were successfully traced to drips in Barker Ranch #1 Cave (Figure 2). The initial injection of KBr in site 1 resulted in a clear breakthrough of bromide, first arriving within three to seven hours, and a later breakthrough of potassium following a second rain event (Figure 3). A number of nearby caves descend below the elevation of drips within Barker Ranch #1 Cave, and are expected to serve as breach structures to funnel vadose flow below the studied drips. Most injection sites were small soil-filled depressions and open solution cavities where runoff naturally localizes and infiltrates. However, site 5 was intentionally selected as a soil site devoid of obvious macropores or depressions. The drip horizon outcrops within 120 m (400 ft) to the east, north, and south of Barker Ranch #1 Cave.

Two chemical tracers tested on Barker Ranch #1, potassium iodide and sodium chloride, were found unsuitable for tracing here and were not reapplied. Background concentrations of chloride in the drips were too high to be able to distinguish breakthrough concentrations on the order of 0.1 mg/l. We were unable to locate a local laboratory to analyze for iodide.

The organic tracers were not detected in Barker Ranch #1 after four injections. In two cases (sites 4 and 6) associated chemical tracers were not detected above background concentrations, indicating that those injection sites are not within the subsurface catchment area to Barker Ranch #1. In the remaining two cases from sites 2 and 3 that were traced to Barker Ranch #1 chemically, it is possible an insufficient mass of organic tracer was injected and the tracers were sorbed by soils and organic-rich materials. Sometime less than a

month after pyranine was injected at site 4 on May 27, 2007, pyranine was measured in a charcoal receptor in well 58-50-511, which is 5.3 km northeast. This is a reasonable hit since that well has had periodic tracer hits from upgradient traces. The well is mapped to be downgradient along groundwater flow paths near Barker Ranch #1, and three-week interval background receptors placed in the well since March 12, 2007, did not detect the tracer.

Based on the tracing results, local breach structures, drip characterization, and drip elevation, an area encompassing the subsurface catchment area was mapped (Figure 2). This area could potentially be further constrained by additional traces.

2009 McNeil Drive Study

Surface geology mapping, subsurface mapping in caves, two borings, and one core allowed subsurface mapping of geological framework expected to influence groundwater flow. All of the caves studied were developed within the Grainstone and underlying Kirschberg Members of the Edwards Group. Maximum stratigraphic dip was measured to be northwest and no faults were mapped between the caves (Figure 4). The subsurface catchment area was mapped based on the cave footprint, a minimum hydraulic gradient of 10% from the mapped cave drips. The presence of one persistent and relatively deep discrete drip in the Rhadine Room of McNeil Bat Cave necessitated including a possible subsurface catchment area to the outcrop of overlying rock in the updip area as far as 600 m (2,000 ft) to the southeast. In this case, the application of tracers might help further refine the subsurface catchment area to a smaller area. The subsurface catchment areas for Fossil Garden, No Rent, and Weldon caves could be adequately delineated to a reasonable area based on outcrop of overlying rock in the updip area and hydraulic gradient from the mapped cave drips.

Three borings encountered groundwater within both the Dolomitic Member and Walnut Formation, beneath the elevation of the studied caves. Although the study of groundwater flow beneath the preserve caves was beyond the scope of the study, the elevation of groundwater within the Dolomitic Member and presence of spring-fed Walnut Creek to the south and southwest of the study site suggest that the perched groundwater is flowing south or southwest, which is surprisingly in the measured updip direction (Figure 4). This evaluation



Figure 2. Tracer injection sites associated with Barker Ranch #1 Cave drip study. Note the subsurface catchment area interpretation is constrained by the surface elevation corresponding to the cave drips, by 6 vadose trace sites, nearby caves that serve as breach structures, and 10% minimum hydraulic gradient for the Grainstone and Kirschberg Members overlying the drips.



Figure 3. Concentration breakthrough in Barker Ranch #1 Cave drip of potassium bromide (KBr) tracer injected in a small soil-filled depression (site 1, Figure 3) about 30 m from the entrance. The injection was flushed by a natural rain event. Bromide peaked three to seven hours after injection. Sampling resumed for a second event after a nine-day pause and sampling detected a late potassium pulse breakthrough.



Figure 4. Geologic cross section of McNeil Drive Site, through No Rent Cave. Since the persistent drips could potentially be supplied in part by a water-quality pond that captures storm-water runoff, the subsurface catchment area was extended to include the entire contributing surface catchment area for the pond.



Figure 5. Geologic cross section of Davis Lane and Subsurface Catchment Area to Balcony Room Drip of Blowing Sink Cave.

of groundwater flow within the Dolomitic Member below the studied drips is not definitive without further study. It is possible the groundwater encountered in the borings is not hydraulically connected, but may suggest exceptions to the general rule of downdip perched groundwater flow.

2012 Davis Lane Study

The location and characterization of cave drips in Goat, Maple Run, and Blowing Sink caves was initially accomplished by observing the inside of the caves after an intense hurricane-related storm in 2010.

Geological mapping indicated that much of the surface in the study area near Davis Lane was underlain by the permeable Leached and Collapsed Members. A shallow depth below the surface, the Regional Dense Member (RDM) was present (Figure 5). The RDM was observed in Maple Run Cave and at a lower elevation in Blowing Sink Cave. While the clay-rich RDM tends to locally perch groundwater, a number of local caves were mapped to descend through and below the RDM, effectively acting as drains to allow the perched groundwater to descend toward the phreatic zone.

Seven surface locations were selected for tracing. Tracers injected into Winterwoods and Sunspot caves were both detected in the phreatic cave stream for Blowing Sink Cave. Tracers injected in Wade Sink and Hideout Sink were both detected in the vadose Balcony Drip of Blowing Sink Cave three days after injection. This drip is approximately 900 m (3,000 ft) south of the injection sinks. It appears that groundwater perched over the RDM, descending through a breach in the RDM at Blowing Sink Cave.

Hydraulic Gradient

Based on the vadose traces included in this study, minimum hydraulic gradients for various hydrostratigraphic units of the Edwards Aquifer can be characterized. Table 2 below shows the measured results through the tested units.

Based on the testing thus far, minimum hydraulic gradients in the Leached/Collapsed and Regional Dense Members are 3%. Higher minimum hydraulic gradients of 12% were measured in the Grainstone and Kirschberg Members, and lower minimum hydraulic gradients of 0.4% were measured across the Walnut Formation. We use 10% in place of 12% for high permeable units both for ease of calculation and because it is more conservative. Although the Dolomitic Member has not been tested yet, observations of water perching laterally over 90 m (300 ft) in Flint Ridge Cave over the rhythmic beds of the Dolomitic Member, and overall perching of groundwater observed in Midnight Cave, Blowing Sink, Backdoor Springs, and Bee Springs, suggest that this unit can have a potentially low minimum hydraulic gradient such as 3%. Like the Regional Dense Member, vertical shafts and fissures that cascade vadose flows vertically are frequently observed in caves developed within the Dolomitic Member

For low permeable units, the source can potentially be very far away, such as the 5 km (3 mi) traces from Buttercup Creek to Blizzard Springs.

Conclusion

The source area to cave drips and cave streams can be delineated using a combination of drip characterization, cave drip elevation and spatial mapping, geologic framework mapping, water-quality characterization, and direct groundwater tracing. Drip characterization

Year	Trace	Hydrostratigraphic Unit(s) Tested	Distance	Depth	Gradient
			(m)	(m)	(%)
1997	Marigold	Walnut Formation	6,116	23	0.4%
1997	Whitewater	ComanchePk/Walnut Formation	5,472	56	1.0%
2007	Flat Depression	Grainstone/Kirschberg Member	26	7	26%
2007	Sister Depression	Grainstone/Kirschberg Member	34	7	19%
2007	Snakehole	Grainstone/Kirschberg Member	67	8	12%
2007	Fieldsoil	Grainstone/Kirschberg Member	65	8	12%
2010	Wade Sink	Leached/Collapsed/Regional Dense Mbr	852	25	3%
2010	Hideout Sink	Leached/Collapsed/Regional Dense Mbr	929	26	3%

Table 2. Measured hydraulic gradients across various hydrostratigraphic units associated with the Edwards Aquifer.

includes measurements in variation of drip rate and spelothem type associated with drip to categorize discrete or seepage source. Non-persistent, widely distributed, soda straw drips may be associated with approximately overlying soil and epikarst drainage. Deeper within the cave systems, discrete drips commonly represent the convergence of smaller flows or a major flow source. Speleothems associated with discrete drips tend to be flowstone cascades, large stalagtites and stalagmites, and rimstone dams. Even where only widely distributed, seepage drips are present, the subsurface catchment area can be assumed to extend at least 100 m beyond the cave footprint, unless direct data suggests a smaller subsurface catchment.

Subsurface catchment areas over highly permeable units, such as the Leached, Collapsed, Grainstone, and Kirschberg Members tend to be smaller than subsurface catchment areas over low permeable units such as the Regional Dense Member, Dolomitic Member, and Basal Nodular Member (identical to the thicker Walnut Formation north of the Colorado River). For the purposes of estimating subsurface catchment areas, minimum hydraulic gradients of 10% can be used to estimate surface extent from cave drips overlain by only high permeable units while hydraulic gradients as low as 0.4 to 3% may be associated with vadose flow over lower permeable units.

Vadose groundwater is generally, but not always, directed in the downdip direction or down faulted blocks. Specific faults, fractures, and fissures may direct parallel groundwater flow within lower permeable units to local discharge sites. In general, it is advisable to extend the subsurface catchment area in the updip or upthrown fault direction to the full outcrop of rocks overlying the drip, even if it exceeds the area defined by hydraulic gradient, unless the source area can be refined by direct tracing. Water-quality characteristics can be used to relate drips of similar source and characterize source areas. Groundwater tracing is the most direct method to associate a surface site and cave drip. Because of the complexities of macropore flow through soils and groundwater flow through the epikarst, vadose, and phreatic zones, a hydrogeological study constrained by conjunctive data such as geological mapping, direct tracing, waterquality sampling, and cave drip surveys delineates the subsurface catchment area with high confidence.

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USE OF PHYSICAL AND CHEMICAL RESPONSE IN CAVE DRIPS TO CHARACTERIZE UPLAND RECHARGE IN THE BARTON SPRINGS SEGMENT OF THE EDWARDS AQUIFER, CENTRAL TEXAS, USA

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Abstract

Cave drips are useful for characterizing recharge and transport through soils, particularly in upland karst settings. Estimation of upland recharge is important for the Barton Springs Segment (BSS) of the Edwards Aquifer, but discrepancies between previous and recent studies indicate how little is known about it in the BSS. We outline a methodology for using cave drips to characterize upland recharge and present initial findings from a study of drips in four BSS caves.

Soils in the BSS are heterogeneous, making it difficult to characterize their hydraulic properties over larger areas, particularly with methods that only yield information about a discrete location (i.e., infiltration tests, moisture sensors). This is particularly true in the BSS where thin, clay-rich, soils often contain macropores (i.e., desiccation cracks, roots, burrows) that act as preferential flowpaths for rapid recharge through the soil zone. Cave drips are well suited for characterizing recharge in upland areas as they often have large source areas.

Drip responses to storm events were monitored at drips in three BSS caves. Hydrograph separation and chemical analyses allowed distinction of fast flow, through macropores and conduits, from slow flow drainage primarily from the soil column. Natural and artificial soil tracers indicate that surface water reaches many of the drips within a few hours of the onset of storm events, even though reported soil Ksat values of 0.06-0.57 in/hr are relatively low, and no discrete recharge was observed within the subsurface drainage basin of three of the caves. These results indicate that upland recharge may contribute a greater portion of total recharge in the BSS than previously estimated, and that rapid recharge can occur in the absence or discrete recharge features likely via macropore flow.

Introduction

Karst aquifers develop in soluble rock where groundwater flows through and enlarges voids by dissolution. They are well known for the development of efficient internal drainage basins that rapidly recharge water beyond the depth of transpiration and evaporation (Jennings, 1985). Diffuse infiltration entering an aquifer through soil and fractured rock is also an important, and often overlooked, source of recharge to karst aquifers (Hauwert, 2009). In fact, in a karst area in New Zealand more infiltration occurred through the soils and macropores than through large sinkhole drains (Gunn 1983). Note herein the term diffuse does not imply that water is flowing through the microscopic pore spaces within the limestone matrix, but refers to other processes including soil drainage, pool storage in open conduits and possibly urban leakage that may cause physical and chemical responses in drips that appear similar to flow through the matrix (Hauwert 2011). To avoid confusion, we use the term "slow flow "to describe this process hereafter.

Soils are often highly heterogeneous, which makes it difficult to characterize their hydraulic properties. Grego et al. (2006) found that 102 test holes, spaced 10 by 20 m across a 3.4 hectare field was insufficient to characterize soil moisture. Other studies have found high variability in recharge over small areas (De Silva, 2004) and variability with topography (Li et al., 2008). This evidence suggests that the portion of recharge to karst aquifers through the soil zone is an important and often poorly quantified source of recharge to karst aquifers.

The ability of water to infiltrate a soil is dependent on several factors including the conductivity of the soil and underlying rock, thickness and structures, initial water content from previous storms and time since onset of the precipitation event (Hillel, 1998). Where soil layers are continuous, the low permeability layers limit infiltration rate, but when soils contain structures such as root holes and macropores, water may preferentially flow through the structures at a rate much faster than would be expected based on the permeability of its limiting layer. Soil tracer tests have revealed that flow through soils is often faster than expected (Quisenberry and Phillips, 1976; Jarvis et al., 1987; Dekker and Ritsema, 1994; Flury et al., 1994; Kelly and Pomes, 1998). Furthermore, the National Research Council (2001) states that, "There exists a body of field evidence indicating that infiltration through fractured rocks and structured soils does not always occur as a wetting front advancing at a uniform rate."

In the BSS there have been conflicting estimations of upland recharge. During a study from July 1979 to December 1982 it was estimated that 85% of rainfall left as evapotranspiration, 9% left as surface runoff, 5% recharged through major creeks and 0.9% recharge occurred in the intervening areas between the major creek channels (Slade et al., 1986). The estimated upland recharge value is significantly smaller than values measured in other karst areas around the world, in the adjacent Trinity Aquifer, and by (Hauwert, 2009). Hauwert (2009) points out potential sources of error in these estimates including lack of continuous discharge measurements upstream and downstream of the recharge zone, no direct evapotranspiration measurements, estimation of runoff coefficients (rather than direct measurement) for the intervening outcrop area between the creek channels, and an incorrect assumption of the size of the recharge area draining to Barton Springs.

A multiple year water balance performed at two upland sinkholes in the BSS indicated that the percentage of recharge occurring in the uplands is significantly higher than originally estimated (Hauwert, 2009). Another key finding of the study was that 26-34% of the rainfall infiltrated though the soil at one of the study sites. This is significant as upland soils in the BSS are often considered to somewhat impermeable and significant barriers to groundwater recharge.

Study area

The study area is located in the Recharge Zone of the BSS and is underlain by the Edwards group that is comprised of extensively karstified Cretaceous limestone and dolomite units in which many sinkholes and caves have formed. Four caves were monitored during two separate studies: Barker Ranch Cave in 2007 and three caves located near Deer Lane in south Austin (Blowing Sink Cave, Goat Cave and Maple Run Cave) from 2010 - present (Figure 1). The caves occur within the Leached and Collapsed, Regional Dense, Grainstone, Kirschberg, and Dolomitic members of the Edwards group. The Leached and Collapsed, Kirschberg and Dolomitic Members are highly karstified, hydraulically connected units that contain many of the known caves and recharge features in the area. The Regional Dense and Grainstone members are much less permeable, more resistant to weathering and water perches and flows laterally across the top of these beds until a breach is encountered (Hauwert 2009).

The caves selected for this study are located on City of Austin Water Quality Protection Lands. Because we focus on upland recharge through soils, Blowing Sink Cave will not be discussed further as several nearby sinkholes recharge it. The subsurface infiltration catchment area of Goat Cave (GC), Maple Run Cave (MR) and Barker



Figure 1. Overview of study area.

Ranch Cave (BR) have been delineated (Hauwert and Cowan, 2013) and no discrete recharge features, such as sink holes or open apertures in the bedrock, are known to exist within their catchment areas. The majority of the delineated catchment areas are overlain by soils, and at Goat Cave and Maple Run Cave, by some impervious cover (roads and houses).

Methods

Chemical and dye tracer arrivals times and the natural geochemical response of several drips were monitored in the caves during two studies. A total of nine traces were completed at BR and three at GC and MR. Chemical tracers (KBr, NH_4CO_3 , and an aqueous Fe solution), fluorescent dyes (Pyranine and Direct Yellow 96), and an optical brightener (Tinopal) were also used to determine recharge source areas and travel times to cave drips. Tracers were applied to soils overlying the caves and flushed through the soils into the vadose zone by natural

rain events (Table 1, Figure 2, Figure 3). Fluorescent dyes in cave drips were detected using activated carbon receptors and optical brighteners were detected using unbleached organic cotton receptors. Chemical tracers were sampled using automatic samplers set at intervals ranging from 4 to 6 hours. Surface runoff samples were collected for comparison to cave drips to help determine drip sources and travel times. Analyses of fluorescent dyes and optical brighteners were performed at the Ozark Underground Laboratory in Protem, Missouri and chemical analyses were performed at the Lower Colorado River Authority Environmental Laboratory Services facility in Austin, Texas.

Driprate was measured continuously at three drip sites BR-Main, MR-Fissure and GC-Main. Driprate was not measured continuously at MR-Waterfall as the discharge at that site greatly exceeds the capacity of the tipping buckets during rain events. To collect enough drip water



Figure 2. Summary of tracer injections at BR.



Figure 3. Summary of tracer injections at GC and MR.

Table 1.	Tracer injection	and detection	summary.	Injection	locations	correspond to	locations	shown or	n Figure	2
and Figure	3.									

Date Injected Injection Location		Tracer Injected	Detection	Arrival Time	
3/13/2007	1	KBr	BR-Main	4-7 hours	
3/14/2007	2	NaCl	Inconclusive		
3/14/2007	3	N _{H4C} O3	BR-Main	~ 48 hours	
5/27/2007	4	Pyranine and KBr	None		
5/27/2007	5	NH ₄ CO ₃ and KI	Br-Main NH ₄ CO ₃	< 26 hours	
5/27/2007	6	NaCl	Inconclusive		
9/3/2007	20072Direct Yellow 96 and Fe		BR-Main Fe	2 hours	
9/3/2007	6	NH ₄ CO ₃	None		
9/3/2007	3	Pyranine and KBr	Inconclusive		
1/25/2012 7 Tinopal and		Tinopal and Fe	GC-Entrance	12 days*	
1/8/2013	8	Pyranine and KBr	None		
1/8/2013 7		Tinopal and Fe	GC-Entrance and MR- Waterfall	<8 days*	

*Dye detected on passive cotton sampler deployed for 1 or more weeks. In process of analyzing water samples taken at more frequent intervals to determine arrival time.

for chemical analyses, small clusters of active drips were monitored at each of the sites. Plastic tarps were used to direct drip water into a collection apparatus consisting of a funnel connected to a sonde flow through cell (physiochemical parameters), that discharged into a tipping bucket gauge (flow rate) followed by a plastic sampling container from which automatic samplers could collect water samples. At MR-Waterfall, a small tarp was used to direct flow into a five-gallon bucket so that an automatic sampler could collect samples and a sonde could record physiochemical parameters. All components coming into contact with drip water were cleaned in a three-step process using distilled water, laboratory soap, and deionized water. Some gaps in drip rate data exist due to logger failures.

Hydrograph and chemograph separation and tracer arrival times were used to determine when breakthrough of recharging water occurred at various drip sites. Chemograph separation was conducted using changes in Mg/Ca and Sr/Ca in dripwater. These ratios fluctuate based on the extent of water-rock interaction, which is controlled by flow rate (Musgrove and Banner, 2004). As residence time increases, progressive water-rock interaction increases the Mg/Ca and Sr/Ca ratios due to incongruent dissolution of dolomite and precipitation of calcite (Figure 4, Musgrove and Banner, 2004). In the vadose zone, residence time is controlled by flowpath, which can be conceptualized as being either conduit flow, meaning short residence time with little chance for water-rock interaction, or slow flow, which is characterized by long residence time with more extensive water-rock interaction.

Results Tracer Arrival

Several tracer breakthroughs were detected whereas some tracers were never detected (Table 1). At BR, tracers typically arrived at the monitoring sites within a few hours of application to the soils (Figure 5). Tinopal has been detected at MR-Waterfall and GC-Entrance by cotton receptors within days of injection. Water samples are taken at more frequent intervals (typically daily during tracing) than the cotton receptors are changed (typically weekly during tracing). Water samples that were collected during the interval that cotton receptors testing positive for Tinopal were deployed will be analyzed to further constrain tracer arrival times.



Figure 4. Geochemical changes caused by increased residence time as measured in vadose and phreatic waters of the Edwards Aquifer. From Musgrove and Banner 2004.



Figure 5. Breakthrough of Bromide tracer measured at BR-Main within a few hours of application to the soil.

Driprate Response

Driprate responded rapidly (within a few hours of the onset of rainfall events) at the MR-Main and GC-Main drip sites (Figure 6). MR-Fissure had a delayed drip response to storm events (Figure 6) indicating that that drip has a more slow flow source than other monitored drips. An automatic sampler collected samples at one site in MR where driprate was not monitored (MR-Waterfall) due to the very large volume of discharging at that site. Based on our observations, MR Waterfall appears to be connected to a water quality pond located approximately 10 meters away as responds within a couple hours of water entering the pond. There are no discrete recharge features (i.e. sinkholes) within the source area delineated for MR and GC but there are some features within source area of BR; however, tracers applied to the soils in the BR source area were recovered at BR-Main.



Figure 6. Representative driprate responses to rainfall events at MR-Fissure, GC-Main and BR-Main.

Geochemical Response

A response in the trace element rations (Mg/Ca and Sr/Ca) to storm events was observed at all sites monitored. This response was more pronounced at Barker Ranch than at Goat Cave (Figure 7). A decrease in the ratios was observed several hours after the onset of the rain events and subsequent increase in driprate. The decrease in trace element ration is interpreted shorter residence time water (related to the rain event) reaching the monitoring sites.

Discussion

The lack of discrete recharge features within the mapped source area of MR and GC indicates that recharge to the caves is likely occurring through the soil and epikarst and not through discrete features such as sinkholes or solution cavities. The rapid drip rate response observed at BR-Main, GC-Main and MR-Waterfall suggests that recharge through the soils and epikarst is quite efficient. Examining driprate response alone is not sufficient to prove that rapid soil infiltration and transmission through the epikarst is occurring. It is well documented that pressure waves can rapidly propagate through the vadose zone and cause a rapid increase in driprate that is not associated with the arrival of recently recharged groundwater. To gain a better understanding of how rapidly recharge is occurring one must examine driprate response in conjunction with geochemical response and tracer arrival times.

With a variable flow rate that is highly responsive to precipitation events, BR is characteristic of a system dominated by conduit flow. Driprate increases of several thousand ml/hr have been observed over a period of hours (Figure 6). Anecdotal evidence suggests that there is some component of slow flow at Barker Ranch drip as the site has continued to drip, albeit slowly, through a recent two year drought period. Also recorded driprate data shows that a baseflow component is present at the site. Dripwater Mg/Ca and Sr/Ca values at Barker Ranch respond significantly to storms (Figure 7). For example, over a five-day period Mg/ Ca and Sr/Ca are strongly correlated with drip rate response to a single day storm. Prior to, and during the initial few hours of the storm event, Mg/Ca and Sr/Ca ratios remain relatively high, suggesting that the dripwater emerging at that time had experienced greater water-rock interaction. Samples taken two days after the event had the lowest Mg/Ca and Sr/Ca values, whereas samples taken 4 days after the storm event had increased to near pre-storm values (Figure 7). This is consistent with the water-rock interaction model in that waters sampled previous to and during the early part of the storm event underwent more extensive water-rock interaction and likely represent the flushing of "older" vadose waters by the rapid infiltration of storm water. Four days after the storm event Mg/Ca and Sr/Ca returned to pre-storm values.

These temporal variations suggest that Barker Ranch dripwater is sourced by a small slow flow component overprinted by conduit flow during storm events. Similar but somewhat muted geochemical responses were observed at GC-Main (Figure 7). Chemical tracers that were applied to the soil near BR were detected multiple times BR-Main and these chemical tracer arrivals typically occurred concurrently with decreases in trace element ratios. Tinopal detections occurred at MR-Waterfall and GC-Main but the arrival time of those tracers will require further analyses to better constrain arrival times (Table 1).

Optical brighteners and dyes applied simultaneously with chemical tracers were never detected in BR, even



Figure 7. Geochemical response to rainfall events at BR-Main and GC-Main.

when chemical tracers were. The optical brighteners and dyes have a high affinity for clay particles and were likely adsorbed by the clay rich soils overlying the study area. Optical brighteners that were applied to the soil near GC were detected at GC-Entrance and MR-Waterfall. Much of the Tinopal was likely adsorbed by clay particles in the soil similar to dyes applied to the soils near Barker Ranch; however, a greater mass or Tinopal was applied near GC than was previously applied at BR, resulting in some of the Tinopal penetrating through the soil zone and into GC. Some of the Tinopal applied near GC was washed down a drainage and into a retention pond that overlays MR (Tinopal could be seen in the water flowing into the retention pond). The pond is lined by thick, locally sourced soils, yet Tinopal was detected in MR-Waterfall, suggesting rapid infiltration through the soils.

The rapid driprate, geochemical response, and tracer arrival times indicate that water is rapidly recharging through the soil zone. Soils in the study area are clay rich and have low Ksat values ranging from 0.06-0.57 in/hr (USDA, 2012), suggesting that such rapid recharge is not possible. Because the soils are clay rich, they shrink and swell with continual wetting and drying. This shrinking and swelling can creates macropores, which are visible on the surface during dry periods (Figure 8).

When soils contain structures such as root holes and macropores, water may preferentially flow through the structures at a rate much faster than would be expected based on the permeability of its limiting layer. Soil tracer tests have revealed that flow through soils is often faster than expected (Quisenberry and Phillips, 1976; Jarvis et al., 1987; Dekker and Ritsema, 1994; Flury et al., 2994;



Figure 8. Macropore observed near Barker Ranch. Representative of macropores found throughout study area when soils are dry. The macropore was not enlarged but vegetation was removed to better photograph. Note cell phone is approximately two inches tall by one inch wide.

Kelly and Pomes, 1998). It is likely that macropore flow is responsible for the rapid recharge of storm water observed in the study area despite the lack of discrete recharge features within the mapped source areas of MR and GC. Our findings suggest that monitoring cave drips is an effective method for characterizing recharge through soils in karst settings.

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THE NEED FOR PRESUMPTIVE HABITAT CONSIDERATIONS IN WORKING WITH SUBTERRANEAN AQUATIC SPECIES OF CONCERN: THREE OZARK REGION CASE HISTORIES, U.S.A.

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Abstract

Delineating habitats for aquatic species of concern present in groundwater systems, and especially those in karst groundwater systems, presents challenges. It is not reasonable to limit the delineated habitat to those portions of a groundwater system that can be directly observed. How then do we make reasonable delineations? Three case histories in the Ozarks region of the central USA illustrate differing approaches for identifying presumptive habitat in recharge area delineations for subterranean species of concern. The first case study of the Tumbling Creek Cavesnail explores the reasoning for designating presumptive habitat downgradient of observed habitat in a cave stream. The second case study of Ozark Cavefish illustrates reasonable designation of presumptive habitat in a complex distributary spring system that discharges water from a well-developed saturated epikarstic area. The final case history illustrates the case for expanding the presumptive habitat in both upgradient and downgradient areas for a Hell Creek Cave Crayfish site in northern Arkansas.

Introduction

Delineating habitats for aquatic species of concern present in groundwater systems, and especially those in karst groundwater systems, presents challenges. It is not reasonable to limit the delineated habitat to those portions of a groundwater system that can be directly searched. How then do we make reasonable delineations? This paper presents three case histories of the use of presumptive habitat designations in recharge area delineations.

Presumptive Habitat

The habitat of a species is most often identified by direct observation or capture. This method is severely limited when dealing with subterranean aquatic species. Even caves generally provide only a small area of access to a much larger groundwater system. Presumptive habitat is the concept that all groundwater with subsurface hydrological interconnections should be presumed to contain the species of concern that is found in accessible portions of the system (Moss and Aley 2003). Implicit in this concept is the assumption that the conditions (temperature, salinity, pH, etc.) in the interconnected groundwater are compatible with the survival of the species in question. This concept allows for more realistic evaluation of the habitat for subterranean aquatic species of concern.

It is important to distinguish the recharge area from presumptive habitat. In most cases, the entire recharge area should not be included as presumptive habitat for the aquatic species. In many cases characteristics of the species in question indicate that certain portions of the recharge area would not be expected to contain the species of concern. Although the entire recharge area for aquatic species should be managed to maintain good water quality for the benefit of the species of concern, the recognition of the probable extent of species habitat beyond an area of direct observation is important for the effective management of subterranean aquatic species of concern.

Tumbling Creek Cavesnail, Protem, Missouri, USA

The Tumbling Creek Cavesnail (*Antrobia culveri*) is federally listed as endangered under the provisions of the Endangered Species Act. The only known habitat for this aquatic cavesnail is the stream in Tumbling Creek Cave in southeastern Taney County, Missouri (McKenzie 2003). As a result of litigation, the U.S. Fish and Wildlife Service was required to designate critical habitat for this species. A hydrogeologically based determination of the area that constituted critical habitat for this species was needed. Tumbling Creek rises in, and flows through, a major portion of Tumbling Creek Cave. Humanly accessible portions of the cave are in the lower members of the dolomitic Cotter Formation of Ordovician age. A locally massive chert unit with a typical thickness of about 1.2 meters (3.9 feet) lies beneath the known cave passages. While dolomite is relatively soluble in groundwater, chert is relatively insoluble. Water passing through a fracture in dolomite will, through time, enlarge the opening by solution. In contrast, the passing water will be much less effective in enlarging a similar fracture in the chert.

The distance from the bed of the cave stream to the top of the chert unit varies from about 0.5 to 3 meters (1.6 to 9.8 feet). At the upstream end of perennial flow in the cave stream the water rises through a solutionally widened joint in the dolomite that almost certainly overlies a major fracture in the underlying chert. The water is rising under pressure up through the chert bed and then flows in the cave stream above the chert. A tributary stream that joins Tumbling Creek in the cave rises through a pool that apparently overlies another fracture in the chert unit.

The weir at the stream gauging station in the cave is about 595 meters (1,952 feet) upstream of the Bear Cave entrance to the Tumbling Creek Cave System. Flow rates of about 0.12 cubic meters per second (cms) at the weir are needed before any flow in the cave stream will discharge through the Bear Cave entrance. Water lost from the channel of Tumbling Creek moves downward through fractures in the chert into dolomitic units that underlie the chert unit. The sinking segments of the cave stream are highly localized and most are within 150 meters of the Bear Cave entrance. The largest single flow loss zone is about 60 meters (197 feet) upstream of this entrance.

With the exception of the Bear Cave entrance to the cave (which is above the chert unit), all of the springs that drain the cave and the accessible portions of the snail habitat derive almost all of their water from flows that have been confined by the chert unit. There are two perennial springs about 730 meters (2,395 feet) apart that drain the cave. Perennial flow is also present in a karst window located between the Bear Cave entrance and most of the springs.

Under high flow conditions the cave is drained by 15 to 20 springs depending upon how one counts springs that are relatively close to one another. These springs are located along 1,585 meters (5,200 feet) of surface stream channels. The range in elevation of these springs is 15.7 meters (51.4 feet). Under high flow conditions tracer dyes introduced into Tumbling Creek in areas near the Big Room will subsequently discharge from all of the 15 to 20 springs. Under high flow conditions groundwater travel rates in excess of 3 meters (9.8 feet) per minute have been documented. The relatively insoluble nature of the chert is the reason for the large number of springs. Under high flow conditions none of the fractures in the chert unit have sufficient capacity to discharge all of the water (up to 4.25 cms) that passes the weir in the Big Room.

Flow beneath the chert unit between the cave and the springs is through a matrix of solutionally widened and interconnected openings localized immediately beneath the chert unit. This distributary flow network explains the large number of springs draining the cave and the rapid groundwater flow rates that have been demonstrated by tracer tests. This area provides presumptive habitat for the cavesnail.

The karst groundwater system beneath the chert unit is not humanly accessible so no survey can be conducted in that area to verify the presence of cavesnails. However, the hydrologic and biologic conditions present for snails beneath the chert unit and hydrologically down gradient of the accessible portions of Tumbling Creek are essentially identical with the conditions found in the areas of Tumbling Creek that are known habitat for the cavesnail. This down-gradient area below the chert unit receives the same water that has flowed through the cave. Bat guano that is an important energy source for the cave ecosystem is flushed into this downgradient area by the stream flow. Flow velocities within the downgradient area are rapid and, like the accessible portions of the cave stream, capable of transporting sediment and organic matter in suspension. As a consequence, during storm events Tumbling Creek and all of the springs are turbid.

The designated critical habitat for the cavesnail (Federal Register 2011) includes all accessible portions of Tumbling Creek within the cave. It also includes as presumptive habitat the springs known to drain Tumbling Creek Cave and most of the lands immediately underlain by the chert unit in locations tributary to the springs. Credible hydrogeologic and biologic data, including the uniformity of conditions, support recognition of this downgradient area as presumptive habitat for the cavesnail and warrant its designation as critical habitat.

Ozark Cavefish, Neosho, Missouri, USA

The Ozark Cavefish (*Amblyopsis rosae*) is a small caveadapted fish that can be found in Southwest Missouri Ozarks into northwest Arkansas and northeast Oklahoma. The Ozark Cavefish is a federally listed threatened species by the U.S. Fish and Wildlife Service. Several population sites have been identified in and around the small community of Neosho, Missouri USA.

Hearrell Spring is located near the Neosho National Fish Hatchery and provides water to the operations there. Due to the presence of Ozark Cavefish in the spring, the Hatchery acquired the spring in 1995 in order to protect the threatened species. Five groundwater traces were performed to delineate the recharge area for Hearrell Spring (Aley and Aley 1997). A recharge area of 14.7 square kilometers (5.67 square miles) was delineated for the spring and consisted of lands in two different Few portions of the Hearrell topographic basins. Spring recharge area contribute water only to Hearrell Spring. All three traces that were detected at Hearrell Spring were also detected at South Big Spring, located approximately 1220 meters (4000 feet) to the northwest. Although not identified in the recharge area report from 1997, the presumptive habitat for the cavefish population in Hearrell Spring would also include lands between Hearrell Spring and South Big Spring. Following this study another spring was identified between Hearrell and South Big Spring. This spring, known as Walbridge Spring, was identified as having Ozark Cavefish in 2006 (Aley et al. 2011). The subsequent identification of a cavefish population in an area that was previously considered to be presumptive habitat based on groundwater tracing provides confirmation of this important hydrobiological concept.

Portions of the Hearrell Spring recharge area are also shared with the recharge areas of four other springs located 1370 to 2130 meters (4500 to 7000 feet) to the east. This distributary groundwater system is draining a well-developed and saturated epikarstic zone. Aley et al. (2007) summarized recharge area delineation results from 24 Ozark Cavefish sites in Missouri, Arkansas, and Oklahoma. They found that 79% of the sites had at least some habitat in epikarstic zones. The epikarstic zone is the weathered upper portion of soluble bedrock units. Its thickness is highly variable, but road cuts near Ozark Cavefish sites in southwest Missouri indicate that it is often at least 6 to 10 meters (20 to 30 feet) thick. The thickness of the epikarstic zone in valleys, and especially those with perennial flow, is generally unknown since highway excavations do not cross them. However, it is likely that typical thicknesses equal and probably exceed those observed in highway road cuts passing through hills. Epikarstic zones beneath the floors of perennial stream valleys are largely saturated with water and, as a result, provide substantial habitat for cave fauna including the Ozark Cavefish.

Dye tracing can yield detections at two or more springs. Distributary spring systems can be common in areas of well-developed epikarst. If one of the springs is known habitat for a species of concern, then it is reasonable to conclude that all of the hydrologically linked spring system should be viewed as presumptive habitat. In the Ozark Cavefish example in Neosho, the springs are draining a saturated epikarstic system. This hydrogeologic condition further supports presumptive habitat within the other springs with hydrologic interactions.

Hell Creek Cave Crayfish, Yellville, Arkansas, USA

A population of the Hell Creek Cave Crayfish (*Cambarus zophonastes*) was discovered in a small spring located along a perennial stream that bisects the small town of Yellville, Arkansas. This troglobitic species is federally listed as endangered and previously known only from two caves located approximately 65 kilometers (40 miles) to the southeast.

The cave crayfish spring, known as Legion Spring, is located along the main stem of Town Branch Creek, just downstream of the confluence of East Prong, a major tributary. The recharge area delineation was performed in 2011-2012 (Kirkland and Aley 2012). Although several good rainfall events did occur that allowed for the introduction of tracer dyes, the study was largely performed under regional drought conditions.

Tracer dyes were introduced in six adjacent topographic basins, including East Prong and Town Branch upstream of Legion Spring. Under the low flow conditions
present at the time of the study, only one of these dye introductions (East Prong) was detected in Legion Spring (Kirkland and Aley 2012). Although gaining stream flow conditions were noted upstream of Legion Spring, groundwater tracing results indicated water from Town Branch downstream of Legion Spring was sinking into the subsurface and recharging two small springs in the adjacent Crooked Creek topographic basin.

Dye tracing indicated the recharge area for the spring with the observed cave crayfish population during the conditions of the study included 18.4 square kilometers (7.1 square miles). However, based upon the setting of the spring in an area of well-developed epikarst on the edge of a valley floor, a larger habitat than the one small spring was reasonable.

Several lines of evidence pointed to a larger presumptive habitat for the cave crayfish population. First of all, well developed epikarst was observed in road cuts and encountered in borings at a nearby petroleum release site. The spring was located on the main branch of a small creek below the confluence of a major tributary. Even though only water from the tributary valley was traced to the spring under the low flow conditions of the tracer study, it is reasonable to expect the cave crayfish population also to be present within the epikarst on the across the small creek. Upstream of Legion Spring on Town Branch is a gaining segment of the creek that drains the epikarst, as evidenced by a healthy population of watercress in the creek immediately downstream of the point where water begins to flow under low flow conditions. Therefore, it is reasonable that the areas of saturated epikarst also be included within the presumptive habitat. Areas downstream of Legion Spring along Town Branch were also included within the presumptive habitat due to the presence of perennial springs with hydrologic interactions with Town Branch below Legion Spring. These downgradient areas were also located under valley floors and expected to have extensively developed and saturated epikarst.

A larger presumptive habitat was reasonable for the observed population of cave crayfish in Legion Spring. The designated presumptive habitat area consisted of 2.2 square kilometers (0.85 square miles) in areas both upgradient and downgradient of the observed population site. In consideration of the larger presumptive habitat, a larger recharge area (18.4 square kilometers or 7.1 square miles) was delineated in contrast to the smaller recharge area for just

the spring site based upon the dye tracing under the low flow conditions (12.6 square kilometers or 4.9 square miles). The expanded presumptive habitat designation and subsequently the larger recharge area provide a more reasonable area for conservation management for species protection.

Summary

From a conservation perspective, the entire recharge area must be managed for subterranean, aquatic species of concern. However, to determine the most appropriate recharge area, the presumptive habitat must be considered in addition to the known habitats of observed populations.

In most cases it is more reasonable to extend presumptive habitat downgradient from a known site than upgradient. This was the case with Tumbling Creek Cavesnail. Hydrobiological conditions support the management of an expanded area downgradient from the known habitat within the cavestream even though direct observation in this area is not available.

Other cases of important presumptive habitat designation include distributary spring systems that drain saturated epikarstic areas. As illustrated by the Ozark Cavefish, it is reasonable that if a known population exists in one spring, populations could exist in other areas with hydrogeologic connections and similar hydroglogical conditions. Presumptive habitat designations in these areas result in identified habitat areas that are often more laterally expansive, and can therefore result in larger recharge areas for the species of concern. Hydrogeologic connections between observed population sites and other springs where the species have not been identified are important to be established during the recharge area delineation of a known population of concern.

In some settings, it is reasonable to extend the presumptive habitat upgradient from a known population site. The recognition of well-developed epikarstic systems, their hydrologic connections through seasonal groundwater fluctuations, and the hydrobiological relationship with subterranean species of concern has led to a presumptive habitat designation that was expanded to include some areas upgradient and down-gradient for the Hell Creek Cave Crayfish in Yellville, Arkansas USA. This larger presumptive habitat is important to identify an adequate recharge area for effective species protection, especially considering the population growth and ongoing development in this area.

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A CHRONOLOGICAL CATALOGUE OF SINKHOLES IN ITALY: THE FIRST STEP TOWARD A REAL EVALUATION OF THE SINKHOLE HAZARD

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Abstract

Among the many different types of geological hazards affecting the Italian territory, sinkholes have often been underestimated (if not neglected entirely), and only in some sectors of the country have they been effectively considered in hazard and risk analysis. Nevertheless, sinkholes affect large parts of Italy, covering the whole territory with a variety of typologies, and exhibit both natural and anthropogenic origin. The latter clearly originate from the long history of Italy, with the complex historical vicissitudes that have characterized this territory, during which different types of artificial cavities have been realized underground for different purposes in different epochs. Over time, many of these cavities have been abandoned, and the consequent loss of memory resulted in their inclusion in newly developed parts of towns, thus creating a serious risk to the built-up environment above.

Starting from these considerations, an archival research was started to collect information about the occurrence of sinkholes in Italy, with particular attention to their precise site and date of occurrence, in order to make an effort in assessing, respectively, the susceptibility and the hazard related to the particular phenomenon under study. As concerns date of occurrence, the accuracy of the information is provided (depending upon the amount of available data), with the highest quality when hour, day, month and year of occurrence are indicated, and a decrease in quality when one or more of these data are lacking. In order to be included in the database, at least some kind of temporal reference (even if general) of the sinkhole has to be known.

The present article illustrates the first results of this study, describing the catalogue obtained so far which consists of more than 650 sinkhole events for which at least some information about temporal occurrence of the event have been found. The data, even though not definitive, represent a good starting point for analysis of the sinkhole hazard at a national scale, aimed at increasing the level

of attention by scientists, practitioners and authorities on this subtle hazard.

Introduction

Italy is affected by a high number of geological hazards that cause severe losses every year and are at the origin of many casualties, thus producing a very high toll to the society. Earthquakes, volcanic eruptions, slope movements, and floods are probably the most wellknown and studied hazards in the country (Guzzetti et al., 1994; Boschi et al., 2000; Gasperini & Valensise, 2000). To these, further phenomena, at least in part caused by man, have to be added: for instance, wildfires, with the consequent effects on loss of vegetational cover and soil erosion.

Within such a framework, sinkholes have often been under estimated if not entirely neglected, and only in some sectors of Italy have they been effectively considered in hazard and risk analysis. Nevertheless, sinkholes affect large parts of the country, covering the whole territory with a variety of typologies, and showing both natural and anthropogenic origin. The latter clearly derives from the long history of Italy, with the complex historical vicissitudes that have characterized this territory, during which different types of artificial cavities have been realized underground for different purposes in different epochs (Parise, 2012). Over time, many of these cavities have been abandoned, and the loss of memory about such features resulted in their inclusion in newly developed parts of towns, thus creating a serious risk to the built-up environment above (Pepe et al., this volume).

When unstable underground caves are located below buildings or infrastructures, their collapse may result in significant economic losses. Further, the rapid evolution of the failure processes (in particular during the catastrophic phase of rupture, and the resulting sudden collapse) can also represent in some cases a risk to human life. In this regard, the high rate of evolution is related to either the propagation of fractures through the intact rock surrounding the caves (Kowalski, 1991; Liu et al., 2000) or the slip movement of rock portions along pre-existing discontinuities, both of these being generally controlled by progressive failure conditions, that sometimes induce catastrophic collapse (Diederichs and Kaiser, 1999a, b; Lanaro, 2000; Starzec and Tsang, 2002; Pine et al., 2006; Parise, 2008; Parise and Lollino, 2011).

Several aspects make sinkholes differ from other types of hazards, such as landslides and flooding: first, a sinkhole is a phenomenon which at the surface appears as punctual (site-located), and that is found at a very specific site, generally of limited dimensions. This, however, does not mean that the affected area is limited to that point, since underground the caves responsible for the event may also show a wide extension. Consequently, sinkholes are rarely taken into account in the analysis of hazard and risk assessment, even though they may represent the main geological hazard in specific settings.

With respect to natural sinkholes, these typically are found in areas with soluble rocks affected by karst processes, or alluvial sediments in peculiar geological situations. Thus, the zonation of the sinkhole-prone areas may be done for natural sinkholes based solely upon geology as a first approximation.

The situation is quite different for anthropogenic sinkholes, because the distribution of artificial cavities depends upon many other factors, such as historical, cultural, and social issues. In this regard, it is important to highlight that we excluded from the catalogue all those events of anthropogenic origin which were reported as due to water leakage from pipelines, with the consequent erosion in the subsoil, without any evidence of an underground man-made cave. Thus, in our catalogue anthropogenic sinkhole means a sinkhole caused by the presence of a cavity created by man underground, regardless of the cavity typology.

In general, there is more detailed information about anthropogenic sinkholes than for those of natural origin. This because the first category generally affects built-up areas, and causes direct damage and negative effects to society (blockage of roads and communication routes, disrupting lifelines, etc.). At least some of these effects are generally reported, which helps in defining the time and site of occurrence of the phenomenon. In the case of natural sinkholes, the related surface effects may go unnoticed, especially when they occur in rural areas; further, land owners often prefer not to spread the news, in order to avoid loss of value of the land.

In Italy, some databases about sinkholes are already available. The most significant are managed by ISPRA and by University of Rome Tre. These databases, however, do not focus in particular neither on time of occurrence of the sinkholes, nor in the distinction between the natural or anthropogenic origin. They are not specifically addressed to assessment of the sinkhole hazard, but rather to indicate the areas of the territory where sinkholes do occur (at the national or regional scale). In several cases they also include unverified information, or a number of cases related to leakage from water pipelines, which may bring to wrong or incorrect conclusions.

To fully evaluate the hazard related to natural danger, the return time of the phenomena needs to be estimated. Lacking such information, there is no possibility to effectively determine the hazard, and the research has generally to stop at the stage of susceptibility assessment (Varnes, 1984). Thus, availability of documentation about past events is crucial.

Unfortunately, very often the record of what occurred even in the recent past is difficult to be found. Further, when some documentation is available, most of the information show low reliability, and are based on memories, or are not supported by real documents. This represents a very important drawback that often has to be faced in the search for historical information on different types of hazards (see, for instance, Calcaterra & Parise, 2001; Glade et al., 2001; Calcaterra et al., 2003).

Actually, it would be useful to better understand the conditions that are likely to cause sinkhole formation (Benson at el., 2003). One of the purposes of this research is to evaluate the timing of sinkholes in Italy, also to provide clues for assessing the specific settings (climatologic, meteorologic, seismic, etc.) under which they formed.

There is a great variety of sinkhole types in Italy (Buchignani et al., 2008; Nisio, 2008; Del Prete et al., 2010; Margiotta et al., 2012), with events triggered by very different factors, including rainfall, seismic shocks and human actions. In fact, even though most of the cases seem to occur in response to meteoric events, and the deriving runoff and groundwater circulation, reactivation of sinkholes may be a consequence of earthquakes too, as recently experienced at the Sinizzo Lake after the Abruzzo earthquake in 2009 (Figure 1; Parise et al., 2010); or be originated by construction of buildings, vibrations due to traffic, or excavations from putting in operation or maintaining the network of pipelines. Further, the interest on sinkholes is increasing in the last years, which has allowed identification of sinkhole features also in geological settings never before considered, such as offshore (see at this regard the work by Taviani et al., 2012).

In the following sections, we will describe the structure of the catalogue, and illustrate the first outcomes, before presenting the future perspectives of this research activity on sinkholes.



Figure 1. Development of cracks along the shores of Sinizzo Lake (Abruzzo), in the aftermath of the Mw 6.3 L'Aquila earthquake, on April, 6, 2009.

The catalogue structure

Based upon the considerations presented in the previous section, the catalogue on Italian sinkholes (Figure 2) has been structured giving a crucial role to the information on time of occurrence of the sinkhole, and, in addition, clearly expressing a level of accuracy about this specific data. Date of the event is subdivided into four different fields, covering hour, day, month and year. Ideally, availability of all data represents the best condition (high category class). Being aware of the difficulties in finding such a detail, we also considered the possibility to have available only a part of the timing information, which in many cases is likely limited to month and year (medium category class). This in particular occurs for sinkholes located in rural areas, where generally no record or observation is recorded soon after the occurrence of the event.

Lacking a temporal reference of the sinkhole, it is possible to use multi-temporal analysis of available aerial photographs and maps to preliminary define a time range (low category class) for occurrence of the event, as shown in the study by Festa and co-workers (2012). In



Figure 2. Distribution of the sinkholes listed in the catalogue over the Italian territory (n = 652). The different colors indicate the degree of certainty in the location: green means certain location, yellow uncertain location, and red very generic indication about the site of occurrence.

first approximation, such an approach allows to get an idea of the time evolution at a particular site. Availability of at least one field among the four dealing with timing is mandatory to include an event in the database. When the event is included, a degree of accuracy is also attributed, with the highest degree corresponding to all the fields being filled, whilst progressively lower information move the degree of reliability toward the lowest values.

This is a very important aspect that strongly makes our catalogue differ from other sinkhole databases in Italy. As aforementioned, we consider of crucial importance the knowledge of the time of occurrence, as a fundamental element to allow an estimate of the likely return time of the events, and therefore to assess the sinkhole hazard.

The sources of historical information include newspaper clips, scientific literature, and critical analysis of the available database on sinkholes. Furthermore, regional and local history books, and transcriptions or translations of old chronicles have also been considered. Some additional information derived from reports prepared by regional and local technical offices to describe the effects of single events and their consequences, and from unpublished technical reports of practitioners. Eventually, our original field data and surveys during the last 15 years provided additional information for some regions of southern Italy (namely, Apulia, Campania, and Calabria). A few bachelor degree theses also dealt with the topic, and were particularly useful for specific areas (for instance, the town of Palermo, with the work by Sottile, 2010). For some recent events, new or updated information was obtained through the Internet, in particular by searching for local daily reports and online newspaper. This is certainly one of the most useful sources nowadays, and has become increasingly used to collect data on a variety of natural hazards.

Regarding sinkholes, one of the few published examples of the use of internet information was recently presented by Brinkmann and Parise (2010). They used two sources of data for recently formed sinkholes in Florida, in the attempt to determine the timing history of sinkholes at Tampa and Orlando: the Florida Geological Society database and the LexisNexis database of newspaper articles. From such sources, a good number of information was extracted on several tens of sinkholes, which allowed the authors to define a model for the timing of sinkholes associated with seasonality, at the same time highlighting the growing public interest in sinkhole formation in the region (Brinkmann and Parise, 2010).

The other fields taken into account in the catalogue refer to origin of the sinkhole (divided into natural, anthropogenic, and of unknown origin), information on the triggering factor, the main morphometric parameters of the sinkhole (diameter, depth), and an indication of the occurrence as first-time event, or re-activation of an already known phenomenon. Regarding origin, sinkholes were included in the "unknown" category when no clear information about the nature of the underground cavities (natural or man-made) responsible for the phenomenon was available.

Damage recorded as a consequence of the occurrence of sinkholes provides very important information. Evaluating damage allows, as a matter of fact, assessment of the effects on anthropogenic structures of a specific hazard, in this case represented by a sinkhole. It is not easy to have a complete figure of the damage resulting from natural and/or anthropogenic hazards: in most cases the information are qualitative, especially for the oldest events. In any case, having the possibility to make a general framework of the damage occurred is a good starting point in the effort to assess the vulnerability linked to sinkholes.

With respect to location, the sites affected by sinkholes were positioned using Google Earth as a base. They were also mapped at 1:25,000 scale, using the topographic base maps by the Italian National Geographical Institute.

The sinkholes are represented (Figure 2) with different colors which indicate the level of uncertainty in location of the event: green is for certainty in the location, yellow for uncertainty, red for very generic indication of the site affected by the sinkhole.

Preliminary evaluation of the catalogue outcomes

In total, 652 sinkholes, for which availability of temporal references has been found, are included so far in the catalogue. Of these, about 100 are anthropogenic sinkholes in the town of Palermo, Sicily, and have been extracted from the work by Sottile (2010), whilst about 150 entries are from the work by Guarino & Nisio (2012) dealing with anthropogenic sinkholes in the town of Naples, Campania, one of the most well known sites in

Italy for sinkhole problems. Overall, more than half of the sinkholes in the catalogue (precisely, 54%) have an anthropogenic origin, whilst a quarter of the entries are due to natural caves, and for the remaining cases no clear origin of their formation has been found so far (Figure 3).

In the catalogue, information on the timing and location of events is generally accurate. Geographical accuracy decreases going back in the past. Historical documents and chronicles are typically more accurate in providing figures for casualties and damage of natural hazards, rather than on their precise location and date (Salvati et al., 2010).

As previously stated, timing of occurrence represents the main information needed for inclusion of a sinkhole in the catalogue. The best situation, represented by availability of all the data concerning time of occurrence (high category class) is satisfied in very few cases (precisely, 22 events, corresponding to 3% of the database; Figure 4). However, if we consider the information where at least the day, month, and year is known, an overall percentage of 68% is reached (high + medium-high categories in the chart in Figure 4). Lower percentages characterize the other categories, where the availability of information about time of occurrence of the sinkhole progressively reduces (medium, medium-low, and low categories).

With respect to the chronological distribution of the sinkholes, the oldest information goes back to historical times for a few cases; some sinkhole events are documented since the 13th century, even though most of the information concentrates starting from the 19th century. For anthropogenic sinkholes, the oldest documented event goes back to the end of the 19th century in Calabria.



Figure 3. Histogram showing the origin of sinkholes in the catalogue: N=natural sinkholes; A=anthropogenic sinkholes; U=sinkholes of unknown origin.



Figure 4. Pie chart showing the percentage of accuracy of date of occurrence of sinkholes.

The events are not equally distributed over time. There is an overall increase in the last decades, which, on the other hand, is not always accompanied by adequate completeness in the temporal information. In other words, it was expected that, moving toward recent times, a higher degree of precision in the temporal information could be reached. Nevertheless, it is very common that, even for recent occurrence of sinkholes, the accuracy in the timing of occurrence may be low. In practice, if the sinkhole is recorded or witnessed soon after its occurrence, and made the object of a description in reports or chronicles, timing is typically accurate; when, on the other hand, the news is obtained later on, only generic information, generally limited to month and year, have to be registered.

As noted by previous scholars dealing with natural hazard catalogues (Guzzetti, 2000; Guzzetti et al., 2005; Salvati et al., 2010), it is very difficult to quantify the incompleteness of non-instrumental records of natural events. Lack of occurrence of events in a given period may in fact either due to catalogue's incompleteness or to changes in the conditions that led to trigger the event (i.e. climate, land-use changes, human actions, and so on).

Information on the location (either precise or approximate) of the sinkhole is available for most of the events in the catalogue. Namely, location of 72% is certain, whilst 21% of the events has some degree of uncertainty, and only the remaining 7% (47 sinkholes) presents a very generic indication about the site of occurrence of the sinkhole.

Sites affected by sinkholes with a chronological reference are not distributed equally in Italy. Their distribution is essentially dependent upon the presence of soluble rocks or alluvial deposits as regards the natural sinkholes, whilst the location of the anthropogenic sinkholes is essentially a function of the presence of artificial cavities. Thus, some towns presents a very high number of phenomena, which is also dependent on a better record of the sinkhole events (this is the case, for instance, of towns as Naples, Campania, and Palermo, Sicily; see Sottile, 2010; Guarino and Nisio, 2012).

Concerning the spatial distribution of sinkholes (Figure 2 and Table 1), some regions show very high numbers, whilst others are much less represented. Two regions (Molise and Valle d'Aosta) out of the 21 in which Italy is subdivided so far do not have any event in the catalogue. This inhomogeneity derives from greater availability of specific works on the topic in particular regions, and/or from direct experience in some others.

Nevertheless, we expect that the future data entry of other sinkholes will in some ways reduce this gap. In any case, it is well known that regions such as Campania,

Table 1. Regional distribution of the sinkholes in the catalogue. The origin of sinkholes is also shown (N=natural; A=anthropogenic; U=unknown).

regions	tot	N	A	U
Abruzzo	22	8	-	14
Basilicata	6	-	-	6
Calabria	8	6	1	1
Campania	246	23	174	49
Emilia Romagna	6	3	1	2
Friuli Venezia Giulia	3	1	-	2
Lazio	107	67	5	35
Liguria	4	3	-	1
Lombardia	1	-	-	1
Molise	-	-	-	-
Piemonte	1	-	-	1
Puglia	88	29	53	6
Sardegna	9	-	3	6
Sicilia	117	1	111	5
Toscana	13	6	2	5
Trentino Alto Adige	1	-	-	1
Umbria	10	-	-	10
Valle d'Aosta	-	-	-	-
Veneto	10	10	-	-
tot	652	157	350	145

Lazio, Sicily and Apulia will be by far the most affected by sinkhole problems, especially due to presence of man-made cavities.

It has, however, to be noted that small numbers in Table 1 do not necessarily correspond to non-occurrence of sinkholes, but rather to unavailability of a temporal reference (which, as before stated, is mandatory for inclusion of an event in the catalogue). In particular, the very low number of anthropogenic sinkholes in Latium (5) has to be noted, given the high frequency of events affecting many towns of this region, including Rome.

For many records in the database only qualitative figures are available about the damage produced. In 17 cases, sinkholes have caused fatalities (the highest toll has been 4 victims in a single event), whilst casualties (deaths and injured people) are documented in at least 26 cases. This is certainly an issue which needs to be better examined, since damage analysis is crucial for assessing the effects to the built-up setting of the phenomena occurred, and the resulting data might be used for delineating different scenarios in case of occurrence of further sinkholes, or re-activations of those already existing.

Apulia (Puglia) region (Figure 5) is here presented as an example of analysis of the catalogue at a higher degree of detail. Choice of the region was dictated by our activity in this territory about sinkholes, and the research we have been carrying out in the last 15 years. The first consequence of the good knowledge of this territory, and of our direct experience in many sinkhole events, is the high certainty in sinkhole location (70 % of the sample; Figure 6); analogously, the accuracy in date of occurrence of the events reaches percentages of 83% for medium



Figure 5. Sinkhole distribution in Apulia region (n=88).

to high accuracy (where medium means knowledge of month + year of occurrence, and high availability also of the hour of the event; Figure 6).

Looking at the chronological distribution of the events, the histogram a in Figure 7 shows that, starting from 1925 (date of occurrence of the oldest documented event in the region, registered at Canosa di Puglia), an almost continuous increase in the number of sinkholes with temporal reference has been observed in Apulia, with slight decreases in this general pattern during the 1960s and 1980s. It has also to be noted that the last bar in the histogram covers a period of less than two years (2011 and the first ten month of 2012).

In the same figure, histogram b is the detail for the time span 2000-2012: with the exception of 2001, 2002, and 2003, at least one sinkhole was documented each year, with a significant increase since 2006, and a





Figure 6. Pie charts illustrating for the Apulia sample (n=88) the percentage of accuracy of date of occurrence of sinkholes (above), and the certainty in location of the sinkhole (below).

small deflection in 2009. This may be in part due to a higher attention paid to the issue, after the first events at Altamura and, especially, that of March 29, 2007, at Gallipoli (Figure 8; Parise & Fiore, 2011; Parise, 2012), and to a more careful record of the sinkhole occurrence. In fact, following the above cited events, the Basin Authority of Apulia (that is, the Regional Body in charge of dealing with hydrogeological hazards and defining the related regulations for land management) issued some



Figure 7. Chronological distribution of sinkholes in Apulia: a) histogram covering the time span from 1925 (oldest documented date) to the present day; b) histogram showing the detailed distribution in the time span 2000-2012.



Figure 8. The March 29, 2007 sinkhole at Gallipoli (Apulia), a recent example of anthropogenic event due to an ancient underground quarry.

regulations specifically to address the evaluation of the possibility of sinkhole occurrence in the case of presence of underground caves, of both natural and anthropogenic origin (Fiore, 2006).

In addition, the increase in attention on sinkholes was also a consequence of the severe crisis occurring at Marina di Lesina (Gargano Promontory, northern Apulia) where, starting from the 1990s, a high number of cover collapse and cover suffosion sinkholes (*sensu* Waltham et al., 2005) were recorded in the gypsum deposits bounding an artificial channel, the result of local hydrogeological changes caused by maintenance works of the canal in the coastal evaporite aquifer (Fidelibus et al., 2011).

Future perspectives

The catalogue of sinkholes here presented represents the first example available in Italy about sinkholes, specifically focused on time of occurrence of the events. At the same time, it differs from other databases on the same topic, for providing a clear discrimination between sinkholes related to natural karst caves (natural sinkholes) and those linked to cavities realized by man (anthropogenic sinkholes). It is our firm belief that the two elements above are of crucial importance for a better understanding of the sinkhole hazard and risk. Knowing dates of the events represents the necessary element for definition of the hazard, whilst occurrence of natural or anthropogenic sinkholes may determine very different scenarios to be faced.

On the other hand, we are well aware that in terms of civil protection issues, it is very important to take into account the analysis of all those events which have caused damage to the society, regardless of their origin as natural or artificial sinkholes. In this sense, collection of data about the intensity of the consequences of sinkholes, with particular regard to number of fatalities and number of casualties appears to be the main goal, since these data are a direct, quantitative measure of the intensity of a disaster, and can be used to evaluate individual and societal risk quantitatively (Fell & Hartford, 1997; Guzzetti et al., 2005).



Figure 9. Examples of sinkholes, of natural (upper pictures) and anthropogenic (lower pictures) origin. Above left: Pianelle sinkhole (Campania region), triggered by the November 23, 1980 earthquake. Above right: one of the many sinkholes in the gypsum deposits of Marina di Lesina (Apulia). Below: sinkholes due to presence of underground quarries at Altamura (left; photo courtesy of CARS) and Cutrofiano (right), both in Apulia.

As next steps, we intend therefore to complete the collection of data of the catalogue, since some regions are evidently less covered than others so far (see Figure 1 and Table 1), and there is definitely space for further data entries. After that, we will perform statistical analyses on the database, to establish the rate of occurrence of sinkholes for the whole Italian territory, and for specific regions or areas that might appear as particularly susceptible to this type of phenomena.

Spatial persistence of sinkholes, that is the occurrence of multiple events at the same site, will also be examined, as a very important element in the effort to evaluate the sinkhole hazard. At the same time, the effects of land use changes, including variations in the flow of surface and ground waters, will represent one of the main issues to investigate, as a likely factor inducing the occurrence of sinkholes.

Further, specific analysis will be performed in urban areas that appear to be the most affected by anthropogenic sinkholes; this is the case, for instance, of Rome, Naples (Guarino & Nisio, 2012), Palermo (Sottile, 2010), but also of many other minor towns in several regions of Italy.

Given the consequences on the built-up areas (Figure 9), the outcomes of the research will be managed in strict collaboration with the Civil Protection Department, aimed at taking into account the sinkhole hazard in a geologically fragile and highly vulnerable territory such as Italy.

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LESSONS LEARNED FROM OCCURRENCE OF SINKHOLES RELATED TO MAN-MADE CAVITIES IN A TOWN OF SOUTHERN ITALY

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Abstract

The presence of man-made cavities below the historical parts of towns is a common feature in large portions of Italy. Different typologies of anthropogenic cavities have been excavated in different epochs for many purposes, including research and collection of potable water, establishment of underground working sites for olive oil production, worship sites, etc. Underground quarries are probably the most diffuse typology of subterranean cavities, especially the largest ones. Originally located at the outskirts of towns, quarries are increasingly found in built up areas due to urban expansion that has characterized the last century.

This paper describes the recent occurrence of sinkholes related to underground quarries in the town of Altamura, in the Murge plateau of inland Apulia, where since 2006 a number of sinkholes have formed above subterranean calcarenite quarries, the local rock mostly used for building purposes. These quarries developed below ground because the calcarenite is generally located covered by clays (ranging in thickness from a few to 15 meters). Their abandonment, and the progressive weathering of the rock, has caused failures in the underground quarries. Eventually, such instabilities propagated upward until reaching the surface, and producing sinkholes.

Many sinkholes in Altamura have occurred within the urban area, and/or in areas of recent or proposed future constructions. As a result, in 2008 the local Authority established a new building code, requiring detailed geological studies in areas determined to be at risk in order to verify and mitigate any hazardous situations. A great amount of data has been collected in these studies in recent years, which has been organized and managed in a dedicated geo-database.

All activities used to identify the underground quarries, recognize the corresponding sinkhole-prone areas at the surface, survey the cavities, produce detailed maps, and reclaim the sites in order to allow future development, are described in this paper, as an example of how to properly manage a territory characterized by sinkhole problems.

Introduction

Altamura (Figure 1) is one of the largest towns in the High Murge of Apulia (south-east Italy), and is located in a foreland area consisting of carbonate rocks where karst is the main agent shaping the landscape (Parise, 2011). In addition to the many karst caves and surface landforms, including the Pulo, one the largest dolines in the region with a diameter of over 500 m and depth of 92 m, there are several cavities of anthropogenic origin at the outskirts of town, in a sector undergoing urban expansion.

These cavities represent a significant risk to the population. Until 2006, it was commonly believed that the subterranean voids were limited to a few areas near ancient open quarries since abandoned and partly filled with solid waste. However, a number of sinkholes have developed in recent years causing safety concerns. Information on these underground man-made cavities has increased greatly in recent years, with over 16 km of subterranean passages explored and mapped.

The present paper describes the methodological approach used to increase the understanding of the caves and procedures have been undertaken to mitigate safety concerns.



Figure 1. Location of the study area.

Geological setting and legal constraints

The man-made cavities that are the proximate cause of sinkhole formation at Altamura consist of underground quarries located at the north eastern and eastern outskirts of town (Figure 2). Their development may be hazardous in this recently urbanized area, where many buildings have been constructed in the last ten years. Only a small number of the buildings date back before 1990, and have been built using surficial foundations. Construction companies did not take into account the underground cavities until sinkholes began to develop. When cavities were found during construction, foundation piles were used to cross the cavities which often produced rock failures within the quarries.

the Murge Highplain and the northern boundary of the Bradano Foredeep (Azzaroli et al., 1968; Iannone & Pieri, 1982; Ricchetti et al., 1988; Ciaranfi et al., 1988; Pieri et al., 1996; Tropeano & Sabato, 2000). The municipality is crossed by the NW-SE topographic divide separating the Bradano River catchment from those of several karst valleys to the east, toward the Adriatic Sea.

The location of this topographic feature divides the Basin Authority of Apulia, covering the northern municipality, and the Basin Authority of Basilicata, covering the central-southern sector, including the urban area of Altamura. The town, located at the top of a ridge at 485 m above MSL, rests on a morphological high of tectonic origin in the Cretaceous bedrock. The areas with underground quarries, on the other hand, are located in a topographically depressed sector where limestones are covered by Miocene calcarenite and Pleistocene silt clays (Figure 3). The calcarenite rock is the object of the underground quarrying activity.

In 2008, following some sinkhole events, the Altamura Municipality issued decree no. 135/2008 obliging all building owners considered at risk to undertake a detailed geological study to verify, and eventually mitigate, all dangerous situations for both public and private properties. At the same time, the Basin Authority of Basilicata issued specific regulations for any new construction, or modification of structures already existing in the areas at risk (Fiore, 2006; Berardi et al., 2010).

These regulations included direct and indirect surveys aimed at ascertaining underground conditions, particularly the presence of voids and instability problems.



The Altamura area rests between the southern portion of

Figure 2. NE outskirts of town, and the underground quarries. Red numbers indicate the documented sinkholes (see also Table 1).



Figure 3. Geological map of study area.

Sinkhole events

Documentation and temporal references have been found for six sinkholes in the Altamura territory (Martimucci et al., 2010; Spilotro et al., 2010; Fiore & Parise, in press). The sinkhole locations are shown in Figure 2, whilst the dates of occurrence are listed in Table 1.

Chronologically, the first documented events (5 and 6) pre-date the year 1947, with no precise date available.

These two events were identified through multi-temporal analysis of aerial photographs. They are located in the same areas where recent sinkhole events have occurred, thus indicating that sinkhole development is a longstanding problem going back at least several decades.

Sinkhole no. 1 was registered at locality Chiancone (Via Di Vagno) in 2006 (Figure 4). It occurred near a small building built upon large diameter pilings.

The May 2007 sinkhole at Via Barcellona (no.2; Figure 5) greatly increased concern about sinkholes, focusing the attention of both authorities and the general population. It was triggered by the roof collapse of an underground calcarenite quarry. There was 15 m of clay overburden, which sustained a shallow aquifer. The sinkhole, of circular shape and with a diameter of 2 m at the surface, was 24 m deep, and exposed an area where the underground galleries are closely distributed.

In 2008, two sinkholes were recorded. No precise date is available for the occurrence of the first (no. 3). It is located near Via Copenaghen, and originated due to collapse of a gallery vault which had already experienced previous failures, and that had been filled with earth material.

The second sinkhole (no. 4) occurred on December 3, 2008, in Via Fornaci, and was produced when filling material of an open clay quarry dropped into an old entrance of the underground calcarenite quarry.

id	date	locality							
1	March 2006	Via Di Vagno							
2	May 07, 2007	Via Barcellona							
3	2008	Via Copenaghen							
4	December 03, 2008	Via Fornaci							
5	before 1947	Via Fornaci							
6	before 1947	Via Praga							

Table 1. List of documented sinkholes.



Figure 4. Sinkhole no. 1, occurred in March 2006 at Via Di Vagno.



Figure 5. The sinkhole at Via Barcellona (May 07, 2007; no. 2): this was the main event at Altamura, directly affecting an area of recently-built houses.



Figure 6. The sinkhole at Via Copenaghen (no. 3).

Causes of the origin of the sinkholes

The main causes of the sinkholes at Altamura are both natural and anthropogenic. Anthropogenic activities have often accelerated processes that were occurring naturally. On the other hand, recent construction activities in the area where the underground quarries are located has highlighted a phenomenon that otherwise would have been less noticed.

Lack of ventilation

In most of the cases, access to the underground quarries has been closed off for two main reasons: man-made solid waste fill and collapse of access points. Runoff water also played a role by transporting and depositing material at the entrances, which in turn produced additional loadings over gallery vaults.

Whatever the reason, access closure impeded air circulation in the underground quarries, leading to degradation of the physical and mechanical properties of the calcarenite rock mass.

Water percolation and infiltration

Rainfall runoff is among the most significant factors producing instability in the underground quarries. It is well documented that runoff from the urban area of Altamura is discharged into the old entrances of underground quarries (Figure 7), or in topographically depressed areas.

Transport of solid materials by these waters is erosive and may, over time, change the permeability characteristics of the rock mass. This phenomenon is particularly evident along the stretch of Via la Carrera from Via Bari to Via Cassano, and in nearby areas.

Deep foundations

Pile foundations (Figure 8) have likely contributed to the development of cracks and failures in the calcarenite rock mass; at the same time, they also represent preferential pathways for water flow.

Boreholes focusing runoff water

In a few cases, boreholes below houses have been found to discharge rainfall runoff collecting in areas around the buildings.

Other factors

There are several other factors that can contribute to sinkhole formation, although generally subordinate to



Figure 7. Flooded passage in a calcarenite underground quarry.



Figure 8. Foundation piles within the quarries.

the previously discussed factors. Leakage from hydric and sewer systems is common. At several areas the sewers directly enter the underground quarries; it is well known that contact between waste waters and soft rocks such as calcarenites may have serious consequences in terms of reduction in the mechanical properties of the rock mass (Dobereiner & De Freitas, 1986; Coop & Atkinson, 1993; La Gioia & Nova, 1995).

Vibrations induced by the traffic may also act in amplifying or accelerating the process of degradation in the rock mass.

Eventually, failures and falls from the vault progressively reduce the thickness of the overlying stiff calcarenite, and fill voids with the breakdown deposits. These latter are frequently of a size that can damage the piles sustaining the buildings above.

Methods of study

The methods used for the survey at Altamura are similar to those normally used for geologic explorations. Conversely, we stress that the approach followed in this study, consisting of a systematic application of surface and subsurface investigations, can produce detailed understanding of complex geologic phenomena, in spite of the inherent difficulties presented by subsurface exploration.

All of the applied methodologies were designed to gain access to the underground quarries. Our started conviction was that the precise survey and location of the underground quarries with respect to the built-up areas above was the main priority, before proceeding with the following phases of study. The surveying activities were especially complex in the urban areas where direct surveys were impossible and indirect surveys were logistically difficult. In this area the best results were obtained with indirect analyses carried out in boreholes.

Indirect surveys

Different types of geophysical methods (2D and 3D electrical tomography, georadar, seismic tomography in boreholes, etc.) are available to identify undergound voids. In the Altamura area, the complex geological setting and the high level of urbanization made surveying difficult. Thus, we developed a complex methodology based on those indirect methodologies that, in our opinion, were the most suitable to the studied setting. Due to depth of

the underground spaces (greater than 15 meters) and to the presence of clays (good conductive materials) overlying the calcarenites, the georadar method did not provide good results. Electrical tomography results were much better (Figure 9), especially using systems with 96 electrodes and more than 2000 measurements.

Such methods, however, require large spaces that are not always available, as well as particular care during data acquisition along roads with asphalt, waste materials and pipelines. When the necessary space was not available, seismic tomographies in boreholes were carried out using hydrophone chains. This method produced interesting results. Even though it was expensive due to the requirement to drill properly equipped boreholes, the method produces information of greater detail along the investigated profiles. Further, it is crucial in ascertaining the presence of unknown cavities after the reclaiming operations.

The large amount of data collected in the last few years has demonstrated that geophysical surveys are useful for obtaining information about the presence of underground cavities. Nevertheless, the possibility of wrong indications or not detecting cavities cannot be excluded. For this reason the indirect surveys are not sufficient alone to provide data for definitively excluding the presence of cavities, and thus cannot be used to ensure safety in building design. On the other hand, when compared and integrated with data from other sources and methodologies, they may play a significant role, especially as regards analysis of large areas, and to support decisions.



Figure 9. Example of geophysical survey for the detection of underground cavities.

Caving and topographic surveys

Caving activities were mainly designed to explore and map the underground cavities and related projections at the land surface, in order to verify any possible interaction with the man-made environment. To this end, a surface topographic system was established to precisely locate the accesses of the quarries. Starting from this system, the underground network was then mapped together with the built-up areas.

The caving activities carried out in the territory of Altamura have been crucial for land use planning and control, and in the land management as well. The Register of Underground Cavities has been established at the Altamura Municipality, according to regulations issued by the Basin Authority of Basilicata (Berardi et al., 2010).

In particular, surveys carried out by cavers were compared with land use maps, and the zonation in different areas of risk has been implemented, with the identification of those sectors considered at high risk (classified as R4).

This approach avoids using only geophysical anomalies to locate cavities, which can be inadequate, thus permitting better designs of the stabilization works. Further, survey and graphical representation methods have evolved in the last three years. The documentation on subterranean voids is not simply provided as graphic data, since practitioners and local authorities need extremely precise information to properly work in highly urbanized areas. Therefore, the underground surveys must be accompanied by the surface topographic network.

Data management and models of interpretation

A GIS-based system was used to manage data associated with the underground quarries (Figure 10), and to highlight the most important data. These include plan views of the cave boundaries, which are basic information for planning any operational activities. The precise locations of narrow passages within the subterranean network are critical to choosing optimal sites for filling of underground voids.

Data collection and geo-database implementation

Using data available at the Technical Office of the Altamura Municipality, a geo-database was developed.

Specifically, a protocol for data acquisition was established aimed at putting all the relevant information in a GIS environment, adopting the convention of WGS 84 coordinates. Data have been sub-divided into seven thematic groups (feature datasets) that comprise specific layers of the database (Table 2).

Multi-criteria approach in the definition of the sinkhole spatial hazard

In order to map sinkhole spatial hazards, some criteria of exclusion, repulsion, and attraction (ERA) have been defined by assigning values to the land attributes in the database. In this way thematic maps were created, to which a weight was then given. Such an approach is not only important for describing and characterizing the territory, but is also aimed at determining those areas that are particularly affected by the phenomena and therefore require particular attention, especially with respect to the design of monitoring and/or alert systems.



Figure 10. Screen views of the GIS system implemented for management of the cavity register.

	1
thematic groups	informative layers
CARTOGRAPHY	topography building cadaster (as of 2011)
TERRITORIAL DATA	land use
GEOMORPHOLOGY	lithotypes faults terrace morphology sinkholes
HYDROLOGY	flooding areas endhoreic catchments hydrographic network
SURVEYS	direct surveys stratigraphies indirect surveys anomalies
CAVING ACTIVITY	cave exploration cave mapping recognition of failures excavation direction
CONSTRAINTS	PAI 2010
OTHER DATA	cadastral data protocols technical office data etc.

Table 2. Structure of the thematic groups and related layers.

To summarize, the tools used have been:

- a multi-criteria analysis to identify the most vulnerable areas and develop a zonation based on susceptibility to sinkholes;
- overlay mapping for spatial analysis.

The variables used to define the susceptibility map to sinkholes are:

- 1. Presence of cavities;
- 2. Presence of underground failures;
- 3. Depth of cavities;
- 4. Lithotypes;
- 5. Land use;
- 6. Surface hydrography;
- 7. Presence of faults;
- 8. Seismicity.

Some features such as tectonics and seismicity have not been taken into account because they are not available or homogeneous over the whole area. The multi-criteria analysis (Malczewski, 1999) was carried out using the comparative matrix of coupled informative layers (Saaty, 1980). Through this procedure the following data layers necessary to produce the hazard map were identified:

- Presence of cavities
- Underground failures
- Cavity depths
- Land use
- Hydrogeology

Elaboration and digital overlaying of the individual data layers have produced the sinkhole spatial hazard map (Figure 11). This map is being used to identify the sectors that most need mitigation measures, taking into account all possible interactions between the spatial characteristics and potential susceptibility.

Values with respect to criteria of exclusion, repulsion, and attraction were assigned to each theme with respect to its relative contribution in terms of susceptibility. The coupled themes were put into a comparison matrix, in order to determine relative weights (Table 3).

All the maps are in raster format, and, by assigning them weights, it was possible to sum the pixel values and obtain the sinkhole susceptibility map (Figure 11), with a maximum value of 60 (greatest susceptibility).

Conclusions

The municipality of Altamura, like many towns in Apulia, is underlain by a long underground network of caves that are the cause of sinkhole formation, which threaten the stability of buildings and other infrastructure. Unique to the region, a process of collecting, managing and disseminating data about the underground environment at Altamura has begun, with a goal of obtaining all the information necessary for reclaiming the sites. The data are being managed in a GIS environment. Such data organization is crucial for identifying sites that are most prone to sinkholes. This work provides a starting point to support mitigation measures and appropriate management of a highly urbanized setting.

In a region such as Apulia, which is highly affected by sinkhole problems related to anthropogenic cavities (Delle Rose et alii, 2004; Fiore, 2006; Barnaba et al., 2010), and particularly to subterranean quarries (Parise

	1 - 2	1- 3	1- 4	1- 5	1- 6	2- -3	2- 4	2- 5	2- 6	3-4	3- 5	3- 6	4- 5	4- 6	5-6		WEIGHTS
1 – Cavities map	0	1	1	1	1	-	-	-	-	-	-	-		-	-	4	0.266
2 – Map of failures in the cavities	1	-	-	-	-	1	1	1	1	51	-	-	-	- 2		5	0.333
3 – Land use map	-	0	-	-	-	0	-	-	•	0.5	0	1	ñ.	1	÷.	1.5	0.1
4 - Depht of cavities	-	•	0	-	-	-	0	-	-	0.5	-	-	1	1	-	2.5	0.16666
5- Geologic and hydrologic map	100	-	•	0	- 1	- 1	-	0	-	-	1	-	0	57	1	2	0.13333
6 - Informatic layer	-	-	-	-	0	-	•	-	0	-	-	0	1	0	0		0
					-								1 E I	1	Tot.	15	1

Table 3. Matrix of paired comparison with the weight of the thematic maps (*normalized value on base 1).



Figure 11. Extract from the sinkhole susceptibility map.

& Lollino, 2011; Parise, 2010, 2012), the methodology developed at Altamura provides an example to follow. This is especially true in light of the fact that a new law was recently issued by the Regional Government, that for the first time takes into account the artificial cavities and establishes pre-requisites for possible tourist exploitation of the caves, once their stability conditions have been fully ascertained (Fiore et al., 2011).

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RESTORING LAND AND MANAGING KARST TO PROTECT WATER QUALITY AND QUANTITY AT BARTON SPRINGS, AUSTIN, TEXAS

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Abstract

The Water Quality Protection Lands program was established in 1998 based on a bond proposal passed to protect Barton Springs in the heart of Austin, Texas. Barton Springs is a popular swimming area for citizens and is also home to at least one federally endangered species of salamander. The initial bond called for 6,070 hectares of land to be protected. Land acquisition has benefitted from additional bonds since then as well the use of grants to raise the total acreage to over 10,731 hectares at present. Additional cost saving measures such as the use of conservation easements have allowed these dollars to be stretched further. Science has helped guide the acquisition of land into more productive geographic areas (based on recharge) and helped direct the management of these lands to further benefit water quality and quantity. Land management focuses on ecological restoration of vegetation back to native prairie and savanna ecosystems which provide optimal water yield from the land based upon the inverse relationship between woody cover and water yield. These restoration actions combined with proper karst management protects both water quality and water quantity recharging through these lands.

Introduction

The Barton Springs segment of the Edwards Aquifer is a segment of the much larger Edwards Aquifer approximately 250 kilometers in areal extent (Hunt *et al* 2005) and is located in Travis and Hays Counties, Texas. The aquifer primarily discharges at Barton Springs, which is a collection of four main springs located near downtown Austin, Texas (BSEACD 2003). The springs are home to the federally endangered Barton Springs salamander (*Eurycea sosorum*) and the rare Austin blind salamander (*Eurycea waterlooensis*), which is a candidate for Federal listing as endangered (BSEACD 2003). At the same time, Barton Springs provides base flow for the Colorado River and is a popular swimming destination for citizens as well as a rallying point for many environmental issues in Austin. During the early 1990s, at the crescendo of issues surrounding development and the protection of Barton Springs came a call to protect Barton Springs by additional regulations including the Save Our Springs (SOS) Ordinance (Dunn 2007, Smith 2012,). Several years after the SOS ordinance was passed, bonds were proposed to further protect Barton Springs as part of the City of Austin's water supply by purchasing sensitive land over the recharge and contributing zones in fee title or conservation easement.

Protecting the Land

In May of 1998 the citizens of Austin voted to support \$65 million in bonds that would acquire land "including fee title and easements in the Barton Springs contributing and recharge zones to provide for the conservation and to maintain the safety and quality of a part of the City's water supply" (City of Austin 1998). Additional bonds, grants and other funds since then have raised the entire contribution toward this goal of land acquisition to approximately \$145,000,000. The Water Quality Protection Lands program was created to manage these lands and currently protects over 10,731 hectares.

Fee Simple versus Conservation Easement

The Water Quality Protection Lands (WQPL) Program owns land in two different ways. The first is as any land would be owned by a private individual, also referred to as fee simple land ownership. In this case the land is owned outright with all rights and obligations intact. On such fee simple lands the City can conduct land management and outreach, provide public access, and perform other activities as needed. Such land also requires the use of City funds to conduct operations and maintenance related to managing and protecting the land, including installing and maintaining fences, vehicle trails, gates and other sundry activities. This land can still be condemned by higher levels of government (county, state, or federal government). The other mechanism for land ownership is the conservation easement agreement. Under this scenario the City purchases the development rights and other rights that govern the allowed activities on the land in perpetuity. These are always made with willing buyers as are all real estate transactions related to the WQPL Program. One of the major limiting factors on private property rights required by these conservation easements is the amount of impervious cover allowed on the land (usually between 1 to 2 percent of the net site area). In addition, such easements also have provisions restricting the use of certain pesticides, limits on stocking rates of livestock, a requirement to manage brush on the property and other restrictions.

Such conservation easements cost the City about 50 percent of the real value of the land. Further, such lands require no outlay of City funds for operations and maintenance of the land, as these are borne by the private landowner. However, each easement is visited annually by WQPL staff to confirm compliance with the easement and provide technical assistance as requested. Occasional legal assistance is also needed to administer this work.

Currently, the WQPL protects 10,731 hectares with 3,941 hectares held in fee simple and 6,790 hectares protected by conservation easements. These purchases have resulted in protecting over 22 percent of the Barton Springs recharge zone and seven percent of the Barton Springs contributing zone. Figure 1 shows the location and type of land holdings and their locations relative to the contributing or recharge zones.

Karst Science Enabling Counterintuitive Purchases

The purchase of these lands includes a variety of factors that determine the acquisition priority of each potential property. Most relevant of these for this paper, but by no means the only priority, is the karst science that has led to relatively counterintuitive acquisitions of property far from Barton Springs.

As shown in Figure 2, the Onion Creek watershed has five different watersheds separating it from where Barton Springs discharges prior to reaching the Colorado River. Yet, the WQPL Program has made significant purchases in this watershed The previous assumption that the most proximal creek to Barton Springs must provide the most significant amount of recharge to Barton Springs has been disproven (Hauwert 2009). Dye traces have indicated a significant flow path from Onion Creek, which is located near the southern groundwater divide (BSEACD 2003, Hauwert et al 2004a, Hauwert et al 2004b, Hunt et al 2005,) that separates water feeding the Barton Springs segment of the Edwards Aquifer to the north and the San Antonio segment of the Edwards Aquifer to the south. Studies by the City of Austin's Watershed Protection Department and the Barton Springs Edwards Aquifer Conservation District have indicated the flow rate can be remarkably rapid from this southern boundary of the recharge zone, travelling up to 11.9 km per day to reach Barton Springs under high flow conditions (Hunt et al 2006). This suggests a major groundwater flow route. In addition, relative to other local watersheds, Onion Creek provides by far the greatest volume of water to the Barton Springs aquifer (Hunt et al 2005), with an estimated 33 percent of the total discharge of Barton Springs originating in Onion Creek (Hauwert 2012). This has led to some significant land purchases almost 31km from Barton Springs and near the furthest extent of the recharge zone for Barton Springs.

Land Management

Owning or otherwise protecting land, such as by conservation easements, provides the greatest measure of protection from impacts such as potential pollutant sources and further allows the natural conditions that feed Barton Springs to continue unimpeded into the future. However, simply purchasing the land or rights cannot curtail the transition or succession of land into ecological states that may produce lower water yields than other ecological states. In the central Texas area grassland and savanna can quickly transition into dense woody canopy following invasion by brush species (Fowler and Simmons 2008). Previously such invasions have been reversed over the evolutionary history of the area by the frequent occurrence of natural wildfires, which have been prevented in the post-settlement era (Bray 1904, Smeins and Fuhlendorf 1997).

The concept of an inverse relationship between woody canopy cover and water yield has been demonstrated in the literature from around the world (Thurow 1998, Wu et al 2001, Le Maitre et al 2002, Davie and Fahey 2005, Hamilton 2008, Mark and Dickinson 2008).



Figure 1. Map of land protected by the Water Quality Protection Lands program as of October 2012.

Further, various studies from Texas have shown additional water yield following brush management (Thurow and Hester 1997, Dugas and Wright 1998, Huang et al 2006, Saleh et al 2009, Banta and Slattery 2011). This has not been without controversy (Wilcox et al 2005, Wilcox et al 2008, Wilcox and Huang 2010), but ultimately the conditions that are most ideal for brush management from a water yield standpoint are well represented on the recharge zone lands protected by the WQPL Program: that is, a shallow soil overlaying a highly fractured subsurface where water can quickly be transported underground (Wilcox et al 2006).

The WQPL Program conducts ecological restoration activities on land held in fee simple to restore the ecosystems back to or maintain their native ecological states of grasslands and savannas (Land Management Planning Group 2001, Lady Bird Johnson Wildflower Center 2010). These are the same ecosystems that the literature has demonstrated yield the greatest quantity of water. Work conducted in this regard utilizes a number of tools to manage brush and encourage grass restoration, including mechanical thinning, prescribed fire and native grass seeding. The work is conducted to be as low impact as possible to avoid erosion and other negative consequences on the land.

Balancing water quality and water quantity can be challenging and at times counterproductive, but again the literature has indicated improved water quality under grassland settings compared to other ecological states (Banta and Slattery 2011). In the case discussed herein, the restoration of native grasslands and savanna ecosystems in the recharge and contributing zones has the potential to further protect or even improve water quantity and water quality at Barton Springs.



Figure 2. Map of watersheds in the area protected by the Water Quality Protection lands.

Karst Management

Once the land is protected and opportunities for optimizing the quantity and quality of water are implemented by land management, the last integral action is to protect the function of karst features. Locating and identifying karst features is an important first step, but this also has to be followed up with prioritizing features in terms of potential to transmit water. Logically, features located in streams beds, such as swallets, would rise above typical upland features in terms of absolute recharge (Hauwert et al 2005), but these upland features should not be discounted. For example the WQPL has at least two upland features with internal drainage basins approaching 24 hectares each. Such internal drainage basins can recharge up to 42 percent of the rain that falls within such a basin (Hauwert et al 2005). A swallet by comparison may have a drainage basin measured in square kilometers. That said, a swallet is unlikely to be able to transmit this total volume due to orifice size and capacity (Hauwert 2009)

Streams over the recharge zone in central Texas are frequently ephemeral in nature and under such conditions may not see appreciable flows for several years. Yet the management of karst features in streams frequently has the highest potential for recharging the largest volume of water over the longest time and accordingly receives the bulk of attention on the WQPL. As a case in point, one feature in Onion Creek (Figure 3) has been estimated to take in up to 425 l/s of water while the creek is flowing (Hauwert 2012).

Swallets can have their function impaired by their success in capturing water as this process also brings in substantial volumes of organic matter, sediment and rocks included in the bed load of the streams in which they are located. Over time this debris can plug swallets and negatively impact their function. Over a period of geologic time, such features are likely to close and open in some measure of equilibrium. However, in managing



Figure 3. Photo of a swallet recharging on Onion Creek.

such areas to positively impact the quality and quantity of water reaching a spring on a human time scale, steps must be taken to keep the function of existing swallets in proper functioning condition rather than waiting for formation of new swallets. This is even more of an acute need when additional demands are made on an aquifer without any offsetting decreases in usage or increases in recharge.

The WQPL Program uses a variety of simple techniques to manage such features to maintain their function. Once a swallet is located, it is evaluated to help determine its importance. If it has the potential to provide significant recharge, a grate will be installed above it to help prevent debris from collecting within the swallet.

Further refinement of these grates has resulted in fine debris covers attached externally to these grates. Such debris covers are structurally weak, but are supported by the initial grate and removable without affecting the underlying grate (Figure 4). This has the benefit of blinding quickly with floating organic debris collecting on the fine grates under flood flows (Figure 5). The blinding of the grate then keeps the sediment associated with the initial flood pulses from passing through the grate. Naturally, this also prevents a large amount of water from reaching the feature, however, as this part of the flood flow is frequently of low quality, it is just as well avoided. The grates can then be cleaned manually once the peak of the flow has passed and allow the cleaner portion of the stream flow to be captured. This helps prevent the plugging of such features deep within the swallet such that maintenance of the grates on the surface is usually sufficient to keep the swallets in proper functioning conditions. Prior to the use of these grates it would be

necessary to wait for a dry period to enter the caves and remove any debris plugs from deeper inside the feature.

These swallets likely owe their origin to dissolution by Onion Creek, as they have a strong vertical component (Hauwert 2013). White (1988) noted that caves carrying water through the vadose zone tend to stair step (i.e. have vertical drops), whereas caves formed at the water table tend to have a strong horizontal component. The humanly explored vertical depths of these features are relatively shallow, reaching at most only 9 to 10 meters as creek alluvial infill is excavated. Most of these swallets become constricted and horizontal in nature at the current limits of human exploration.



Figure 4. Example of swallet grate with fine debris cover.



Figure 5. Example of swallet grate with fine debris cover after storm event and prior to manual cleaning.

Once grated, some swallets can then be excavated to remove accumulated sediment with very little accumulation of new sediment. This can allow the unencumbered passage of water with less re-suspension or movement of old sediment. Few terrestrial organisms survive the periodic and occasionally long lasting inundations, but contractors doing such excavations are required to have U.S. Fish and Wildlife Service permits for working with endangered karst invertebrates.

In one example of this sort of excavation, a former landowner who was raised on the property, likely around the 1950s or 1960s, reported a frequent whirlpool originating at a known swallet. No whirlpool had been reported or identified in recent time at this location and dye tracing showed it had a much longer travel time to Barton Springs than did a nearby feature also on Onion Creek (BSEACD 2003), albeit under a different flow regime. It seemed likely that 50 years of floodborn sediment might be preventing this feature from functioning properly. However, it is hoped that removing this sediment in combination with the addition of grates will return this swallet to proper functioning condition. The project is ongoing but over 38 meters³ sediment and debris has been removed to date.

Upland features require much less attention, as they are frequently less prone to becoming plugged by debris, and proper functioning condition is maintained in these features by vegetation management that helps reduce erosion into the features. Frequently, upland features may also be home to karst invertebrates that could be endangered and may require the cave be protected as a refuge for such organisms versus being managed as a recharge feature.

Conclusions

The Water Quality Protection Lands were established to help protect a portion of the City's water supply, namely Barton Springs. The methods of this protection began with the purchase of land and the protection of additional land with conservation easements leading to the protection of over 10,730 hectares.

The WQPL Program went further and is implementing a land management plan to manage the land owned in fee simple to optimize the quality and quantity of water leaving the lands and recharging into the Barton Springs segment of the Edwards Aquifer. Techniques including those associated with ecological restoration are used to restore or maintain the vegetation as native grasslands and savannas, which have been shown to yield greater water than more woody landscapes. Finally, to ensure that water recharging off these lands can continue to benefit Barton Springs, karst features, and especially swallets, are managed and restored to proper functioning condition and protected from sedimentation that could impede or obstruct recharge.

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THE USE OF DROUGHT-INDUCED "CROP LINES" AS A TOOL FOR CHARACTERIZATION OF KARST TERRAIN

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Abstract

The persistent drought of the 2012 summer in the Midwestern United States significantly impacted the health and vigor of Illinois' crops. An unforeseen outcome of the extreme drought was that it provided a rare opportunity to examine and characterize the bedrock surface and underlying karst aquifer within the Driftless Area of northwestern Illinois. Complex networks of vegetated lines and polygonal patterns, herein referred to as crop lines, crisscrossed the dry summer landscape of Jo Daviess County. Initially, the crop lines were examined and photographed using a handheld digital camera on the ground and from a small aircraft at 300 meters altitude above ground level (AGL). The orientations, widths and horizontal separations of the lines were measured. Crop lines and their patterns and orientations were compared with those of crevices in outcrops, road cuts and quarries, and with lineaments seen in LiDAR elevation data of Jo Daviess County.

Primarily confined to alfalfa fields and, to a lesser extent, soybeans and corn, the crop lines are the result of a combination of extremely dry conditions, and a thin soil zone overlying fractured and creviced Galena Dolomite bedrock. The plants forming the lines tend to grow denser, taller (0.5 m vs 0.15 m) and darker/ greener than those in adjacent areas. Alfalfa taproots are the deepest of the aforementioned crops extending up to 7 m below the surface. Groundwater and associated soil moisture within the vadose zone present within bedrock fractures and crevices provide the necessary moisture to sustain the overlying healthy plants, while the remaining area of the field exhibits stunted and sparse plant growth. Overall, the crop lines are a reflection of the creviced pattern of the underlying karst bedrock and associated karst aquifer, and reveal the degree and extent of karstification in eastern Jo Daviess County. The crop lines were consistent with the angular lines of adjacent streams that show a rectangular drainage pattern. Stream patterns like these are well known and are due to drainage controlled by crevice/fracture patterns in the top of bedrock. The lines appear to have been formed by two sets of fractures trending roughly northsouth and east-west with occasional cross-cutting fractures/ crevices. The east-west trending lines are consistent with tension joints, and the north-south lines are consistent with the shear joints identified by earlier researchers. The trends of the crop lines, tension and shear joints are similar to those of lineaments identified from LiDAR elevation data in the same area (N 20° W, and N 70° W and N 70° E) and coincide with the occurrence of karst features throughout eastern Jo Daviess County.

The pattern observed in the crop lines closely mimics the fracture/crevice patterns of the bedrock surface. The widths and extent of the lines may be used as a surrogate for the karst features present on the bedrock surfaces. Crop lines, coupled with solution-enlarged crevices seen in bedrock exposures, yield a three dimensional view of the bedrock crevice-fracture system, and ultimately could provide a more complete and accurate model of the karst aquifer in the study area and similar karst areas in the Midwestern United States and perhaps in other karst regions of the world.

Introduction

Carbonate rock at or near the surface are fractured and typically creviced due to solution enlargement to the point

where the rock body constitutes a karst aquifer (Quinlan et al. 1991). These fractures and crevices are usually covered with fine-grained sediment. Consequently, the fractures and crevices in the bedrock are only observed in excavations, road cuts, quarries, outcrops and rarely where the soil and sediment overlying the bedrock surface has been denuded by erosion. However, in areas where soils are thin and during extremely dry periods and where crops are planted, lines in the vegetation (hereafter referred to as "crop lines") have been observed in the Wisconsin Driftless Area (Maureen Muldoon, University of Wisconsin, personal communications, 2011). It is likely that these lines mirror the fracture/crevice patterns of the underlying bedrock carbonate aquifer.

Unfortunately, the reporting of these occurrences is usually only anecdotal, and documentation is difficult to find because of their ephemeral nature which may be only weeks or a few months. However, in rare cases, researchers succeed in capturing short-lived phenomena. Extreme drought conditions in Illinois and in the surrounding states in the 2012 summer created a rare situation that has resulted in the formation of vivid lines and patterns in crops in Jo Daviess (Figure 1) and surrounding counties in northwestern Illinois' Driftless Area. The crop lines (Figure 2) occurred in the thin soils of the Driftless Area overlying the carbonate bedrock of the eastern two thirds of Jo Daviess County, the western portion of Stephenson County and well into southern Wisconsin.

The objectives of this investigation were to document the crop lines observed in eastern Jo Daviess County, Illinois, and assess their usefulness as indicators of karstified carbonate bedrock that may be associated with a karst aquifer. Because the crop lines appear to accurately mimic the creviced surface of the underlying karst bedrock, we explored their usefulness in identifying the extent, character and geometry of the underlying karst aquifer.

Methods

The authors were contacted by a Jo Daviess County resident on July 16, 2012 concerning the appearance of crop lines in the Driftless Area of northwestern Illinois. We conducted a reconnaissance trip to eastern Jo Daviess County on July 19 during which time we examined and photographed abundant crop lines on the ground, as well as from a low-altitude aircraft using a handheld camera. The initial photography was used to secure funding for additional trips to the site.



Figure 1. Generalized geologic map of Jo Daviess County (modified from McGarry 2000).



Figure 2. Alfalfa fields reveal the geometry and character of the underlying karstified Galena Dolomite. Crevice-controlled rectangular stream patterns are also apparent. This oblique aerial photograph was taken 4.0 km south of Warren, IL in Jo Daviess County.

A subsequent low-altitude reconnaissance flight was conducted one month later to document additional occurrences and estimate the geographic extent of the crop lines in Jo Daviess County. Based upon this information, a request was made to the Illinois Department of Transportation, Aerial Survey Division to acquire vertical aerial photography for 16 selected sites using a 9"x9" mapping camera. However, due to weather issues, aerial photographs were not taken until August 28 and 29. Soon after the IDOT aerial photography acquisition, the area experienced increased rainfall and harvesting began earlier due to the drought. The combination of these two factors resulted in the crop line features disappearing or being eliminated.

Soil depths were measured in lined fields using a soil probe and a tape measure. Vegetation that created the crop lines was examined on the ground and from aerial photography. The widths, orientations and spacing of the crop lines were documented and compared with those of crevices and fractures in exposures, and with lineaments seen in LiDAR elevation data of Jo Daviess County (Panno et al. in review). All imagery and field data were examined and compared with information gleaned from existing bedrock exposures as described by Bradbury (1959), Heyl et al. (1959), and Panno et al. (in review).

Results and Discussion Geology of Jo Daviess County

Jo Daviess County (Figure 1) lies within the Driftless Area of northwestern Illinois; the county lacks glacial drift that covers the bedrock of most of the upper Midwestern U.S. (Hansel and McKay 2010). Bedrock in this county consists of Middle-Ordovician (443 – 490 Ma) carbonate rocks of the Galena-Platteville Group, thin remnants of the Ordovician age Maquoketa shale, and Silurian-age (412 - 443 Ma) dolomite that constitutes much of the highlands in the county.

Tectonic compression and extension occurred in this area during and following the formation of the Wisconsin Arch that began in Cambrian time (490 - 543 Ma) and continued to be active in late Silurian or Devonian time (354 – 417 Ma) (Nelson 1995). The Wisconsin Arch, in part, separates the Illinois Basin to the south from the Michigan Basin to the east. The Mississippi River Arch separates the Illinois Basin from the Forest City Basin to the west. Jo Daviess County lies on the southwestern flank of the Wisconsin Arch (Frankie and Nelson 2002). As a result of the compression and extension, bedrock along the Wisconsin Arch has a well-developed vertical joint system. Heyl et al. (1959) identified that "All the rock formation in the district [most of Jo Daviess County] contain well-developed vertical and inclined joints. The vertical joints are traceable for as much as 3.2 km horizontally, and for as much as 100 m vertically. Joints are especially well developed in the Galena dolomite." Heyl et al. (1959) identify three groups of joints: tension joints trending E-W to N 65° W, and two sets of shear joints trending N 20° -30° E and N 20° -30° W. Bradbury (1959) found that crevice orientations in numerous exposures in far eastern Jo Daviess County trend N 85° -90° W (nearly E-W) and N 02° -18° W.

Solution-enlarged crevices also acted as foci for ore mineralization in this area. The geology of the Upper Mississippi Valley Zinc-Lead District, which includes Jo Daviess County and extends into Iowa and Wisconsin, has been summarized by Heyl et al. (1959) and Bradbury (1959). Lead- and zinc-bearing ore minerals were mined from this area between the late 1700s and 1973. Primary ore mineralization was found in solution-enlarged crevices or in solution cavities in carbonate rocks of the Galena Group called "gash-vein deposits." Galena (PbS₂) was the main ore mineral in these deposits, and sphalerite (ZnS₂) was the most abundant ore mineral associated with bedding planes and reverse faults (Heyl et al. 1959). For these types of ore deposits, hydrothermal fluids (hypersaline brines) carrying lead and zinc in solution were implicated as the source of the mineralization by various geochemical and isotopic indicators within the ore and associated minerals. Oreforming solutions originating from evaporative brines associated with the Reelfoot rift system (late Paleozoic time) is one of the more recent hypotheses proposed

to explain the origin of these deposits (Rowan and de Marsily 2001). Ore mineralization and dolomitization of the Ordovician-age carbonate rocks of this district have been dated by several techniques as Early Permian in age ranging between 270 and 280 Ma (Brannon et al. 1992; Pannalal et al. 2004).

Recent work by Panno et al. (in review) expanded on our understanding of the karst terrain of Jo Daviess County first identified by Weibel and Panno (1997). Examination of the LiDAR elevation data revealed numerous lineaments in eastern Jo Daviess County (Figure 3). Lineaments identified from aerial photography have been used since the early 1950s for oil, gas, and mineral exploration. Lattman and Parizek (1964) and Parizek (1976) extended this work to groundwater resources by identifying and examining major lineaments to define zones of increased weathering, porosity, and permeability within carbonate rock. Specifically, Lattman and Parizek (1964) state that "Fracture traces and lineaments appear to be universal in their distribution and will have their greatest utility in rocks where secondary permeability and porosity dominate and where intergranular characteristics combine with secondary openings influencing weathering, and soilwater and groundwater movement." The lineaments in Jo Daviess County consisted of the alignment of numerous, unusually-oriented stream valleys across the study area. Many stream valleys are linear, while others have sharply angular meanders. These angular features or rectangular patterns are classic geomorphologic indicators and strongly suggest bedrock control of the streams in the study area (Figure 2).

The lineaments in the study area have three distinct trends; approximately N20°W, N70°W, and N70°E. Examination of sinkholes in eastern Jo Daviess County revealed individual sinkholes and *en echelon* sinkholes, all of which are coincident with lineaments. Examination of mapped lineaments in far eastern Jo Daviess County revealed that every lineament had one or two sinkholes in close proximity to one another and to the streams. Sinkholes in this area were typically 0.5 m to greater than 1 m deep and about 1 m in diameter. Larger sinkholes up to 10 m in diameter were also found. Features that were often found associated with the sinkholes were steep-sided, partially water-filled indentations along the stream bank that extended 1.6 to 5 m into the



Figure 3. LiDAR shaded relief image of eastern Jo Daviess County showing lineaments and their orientations (from Panno et al. in review).

bank. In addition, the stream orientation tended to shift abruptly and follow the trend of the lineament where they crossed streams instead of having the more typical gently curved meanders. These angular stream features had similar orientations to the mapped lineaments and reflect bedrock control. On the basis of these data, the lineaments identified on the LiDAR maps are interpreted to be a reflection of open crevices in the underlying carbonate bedrock aquifer that are transmitting groundwater. Examination of the geomorphology of the stream valleys suggests that the lineaments are linear depressions that formed along solution-enlarged crevices. These depressions probably form where overlying sediment becomes thinner with proximity to stream valleys where carbonate bedrock is exposed in the stream floor. Lineaments in carbonate rock terrain have been found to be indicative of zones of enhanced well yields; that is, the use of lineaments (only) in locating highproductivity wells in carbonate terrain has had a success rate of 75 to 80% (R. Parizek, Pennsylvania State University, personal communications, 2009).

Crop Lines

The 2012 summer drought that affected the health and vigor of crops of the Midwestern United States and thin soils provided an opportunity to view the geology of the underlying carbonate bedrock in the Driftless Area of Illinois. Less than 8 m of soil and unconsolidated materials overlie the fractured and creviced carbonate bedrock of Jo Daviess County, northwestern Illinois (Riggs and McGarry 2000). Measurements of soil thickness in the areas between the crop lines at one field ranged from 0.6 to 1.2 m. Soil thicknesses immediately over the lines were typically greater than 1.5 m. Excavation of the lines revealed that many contained clays that were visually and texturally identical to the weathering product of Maguoketa Shale. The depth of the clays within the crevices was at least 3 m for the few crevices examined. The wetness and presence of water within the clays suggested that water was moving through the crevices, perhaps along piping channels.

During the 2012summer, complex networks of dark green vegetation separated by gray patches of nearly bare
ground were observed. These lines of vegetation, often forming complex polygonal patterns with dominant directional orientations, were most pronounced in fields sown with alfalfa, and to a lesser extent, soy beans and corn. The alfalfa forming the lines tended to grow more densely, taller (0.5 m *vs* 0.15 m), and darker/greener than those in adjacent areas. Alfalfa is typically grown on relatively steep slopes to retard soil erosion. These features were visible on Google Earth imagery acquired in September 2012 (Figure 4). Alfalfa is described by the Soil and Health Library (2012) as follows: "Alfalfa is a long-lived, very deeply rooted perennial. Upon germination, a strong taproot develops rapidly and penetrates almost vertically downward. It often reaches a depth of 1.5 to 1.8 m the first season, 3.0 to 3.6 m by the end of the second year, and may ultimately extend to depths of 6.1 m or more. It is notably a deep feeder." Consequently, the alfalfa roots can access the moisture/water moving through bedrock crevices near the top of the karst aquifer. Corn



Figure 4. Google Earth imagery showing the complex geometry of crop lines in an alfalfa field.

and soybean roots tend to have shallower root systems. Corn is a more shallow rooted plant reaching depths of 1.2 m or more. Less than 10% of the water taken up by the corn plant is acquired below 1 m (McWilliams et al. 2004). Soybean plant roots extend to a depth of 1.2 to 2.4 m, with most of the roots being in the upper 0.15 to 0.30 m of soil (North Dakota State University 1997).

The bedrock fractures and crevices provide the necessary moisture to sustain the overlying healthy plants, while the remaining area of the field exhibits stunted and sparse plant growth. In aerial view, the crop lines create polygonal patterns, most of which trend roughly northsouth and east-west; the trends of these lines are similar to the angular lines of the adjacent streams showing rectangular drainage patterns. Rectangular stream patterns like these are well known and due to control by crevice/fracture patterns in the top of bedrock. Streams tend to follow the paths of least resistance. The orientation of the stream channel is consistent with the orientation of crop lines and the straight reaches of the stream follow trends seen in crevices exposed in outcrops, road cuts and quarries (Figure 5). This and the similarity of crop lines with lineament patterns in LiDAR elevation data, and crevice occurrence in outcrops, road cuts, and quarries found throughout eastern Jo Daviess County, western Stephenson County, and northern Carroll County indicate that the lines and patterns observed in the croplands are a direct reflection of the creviced pattern of the underlying karst aquifer. As such, the lines are a surrogate for the solution-enlarged crevices of the underlying carbonate bedrock and reveal the degree and extent of karstification in the eastern part of Jo Daviess County.

Finally, desiccation cracks are almost exclusively located along the crop lines and follow their trends (Figure 6). No cracks in the soil were seen in areas adjacent to the lines where vegetation was stunted and typically about 6 inches high. This phenomenon is probably due to fact that the shallow roots of the crops tend to take up moisture from the soil and create desiccation cracks, but only in those areas were vegetation is thriving.

Ongoing Research

The authors are currently georeferencing and analyzing crop-line length, width, and orientations in detail at sixteen sites in eastern Jo Daviess County, and their relationship with the geometry of solution-enlarged



Figure 5. Road cut through Galena Dolomite and located along Rt. 20 near Elizabeth, IL in Jo Daviess Co. The solution-enlarged crevices are oriented N-S and are 1 m wide (from Panno et al. in review).



Figure 6. Desiccation cracks within and following the trends of the crop lines.

crevices. Preliminary results indicate that the crop lines are dominated by a set of fractures/crevices trending N 5° E and N 80-85° W (approximately north-south and east-west) with occasional cross-cutting fractures, crevices and zones that appear to have been shattered. The east-west trending lines are consistent with tension joints, and the north-south lines are consistent with the shear joints both identified by Heyl et al. (1959). Heyl et al. (1959) further stated that these fractures/crevices extend to a depth of up to 100 m. The trends of the crop lines, tension and shear joints are similar to those of lineaments identified from LiDAR elevation data in the same area by Panno et al. (in review). The trends of the LiDAR elevation data lineaments are N 20° W, and N 70° W and N 70° E; their traces coincide with karst features (cutters and grikes, cover-collapse sinkholes, caves and springs) throughout eastern Jo Daviess County.

Based on the presence and orientations of the crop lines and their relationship to solution-enlarged creviced seen in road cuts, quarries, and outcrops, and lineaments seen in LiDAR elevation data, it is clear that the patterns observed in the crops mimic the fracture/crevice patterns of the bedrock surface. The widths and extent of the lines may be used as a surrogate for the karst features present on the bedrock surfaces. Crop lines, coupled with solution-enlarged crevices seen in the aforementioned bedrock exposures, yield orientations and spacing of solution-enlarged crevices and fractures of the carbonate bedrock. Taken together, these features yield a three-dimensional view of the bedrock crevice-fracture system, and ultimately could provide a more complete and accurate model of the karst aquifer in the study area and similar karst areas throughout the world.

Conclusions

An investigation of crop lines that appeared during the extreme drought of the 2012 summer in the Midwestern United States may provide an additional method for investigating and characterizing karst terrains. The crop lines were noticed by local farmers primarily in alfalfa fields and reported to the ISGS in the summer of 2012. Within days, the crop lines on the ground and from aerial photography. The widths, orientations, and distance of separation of the lines were examined and compared with crevices in outcrops, road cuts and quarries, as well as with lineaments observed in LiDAR elevation data. Subsequent field work focused on character, thickness, and composition of the materials within the crevices.

The crop lines formed in very shallow soils (less than about 1.5 m thick) and are of similar orientation as those of solution-enlarged crevices exposed in outcrops, road cuts, and quarries, and of lineaments seen in LiDAR elevation data of the study area (roughly north-south and east-west). The limited number of crevices examined beneath the thin soils contained clays similar to those of weathered Maquoketa shale. It is likely that these clays have entered the crevices in the upper part of the Galena Dolomite. However, abundant water present within the clay suggests there is piping and movement of recharge and groundwater through the clay.

We conclude that the crop lines may be used as a surrogate for mapping the fracture/crevice pattern on the carbonate bedrock surface. The crop lines are of similar orientation as those of solution-enlarged crevices exposed in outcrops, road cuts, and quarries, and of lineaments seen in LiDAR elevation data of the study area. Crop lines, combined with other data from outcrops, road cuts, quarries and LiDAR elevation data, may be used to identify and characterize the degree and extent of karstification in the carbonate terrain of the Driftless Area on northwestern Illinois, and other karst areas of similar geology. Further research currently is underway.

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MAPPING SURFACE AND SUBSURFACE KARST GEOHAZARDS FOR HIGHWAY PROJECTS: SR 71 SOUTH KNOXVILLE BOULEVARD EXTENSION, KNOX COUNTY, TENNESSEE

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Abstract

The proposed extension of SR 71 (South Knoxville Boulevard) located in Knoxville, Tennessee necessitated a preliminary geologic evaluation of the corridor which was under consideration by the Tennessee Department of Transportation. A geohazards review disclosed the presence of extensive karst terrain located within the corridor being considered. A number of caves were also found during the investigation. The proposed routes within the study corridor were found to cross a series of very large multiple hectare (acre) sinkholes. In addition, a biological investigation of the route revealed the presence of a rare and endangered species of cave salamander called the Berry Cave Salamander.

The geologic and geotechnical investigation resulted in the development of a surface karst map of the study corridor. Sinkholes and cave entrances were located and a generalized karst boundary was established. In addition, a survey map of the Meades Quarry Cave was made which provided supporting quantitative data in connecting surface sinkholes and the cave containing the endangered Berry Cave Salamander. A recommendation of the study was a dye tracing of the suspect sinkholes. If this highway project is constructed, then measures will be required to mitigate the effects of the highway run off in the karst terrain affecting the Berry Cave Salamander.

Introduction

Large areas of East Tennessee are underlain by carbonate rocks such as limestone and dolostone with some estimates of as much as 50% to 60% of all underlying rock types being carbonates. As a result, these areas are subject to solution type chemical weathering and the resulting karst landform development, such as sinkholes and cave systems.

The Tennessee Department of Transportation (TDOT) is planning a new roadway alignment (SR 71) that crosses portions of South Knox County in East Tennessee. The proposed corridor is located in a section of the Valley and Ridge Province of East Tennessee where several ridges and valleys will be crossed, as well as creeks, roads, subdivisions and rural lands (Figure 1). The proposed corridor connects the current terminus of SR 71 at Moody Ave. in South Knoxville to John Sevier Highway (SR 168).

In an attempt to properly evaluate the potential for geologic hazards along the project, an effort was made to locate all sinkholes and caves within the project area, karst being the primary geologic hazard identified. To this effort, a karst map and a map of one cave was completed.

General Geology of Proposed Corridor

The proposed corridor is situated in the rolling to hilly topography of the Valley and Ridge Province of East Tennessee and includes a portion of South Knox County (Figure 2). Geologically, the corridor is situated in terrain underlain by folded and faulted sedimentary strata composed of several major rock types including limestone, shale, sandstone, and siltstone.

The geologic formations that underlie the study area are part of the middle-Ordovician Chickamauga Group and include the Lenoir Formation–Ol (argillaceous limestone), Holston Formation–Oh (marble, crystalline limestone), Chapman Ridge Formation–Ocr (sandstone), and the Ottosee Formation–Oo (shale, siltstone, and limestone). These formations have geologically normal conformable stratigraphic contacts and comprise the major portions of a large flexure anticlinal fold (Figure 3) (W. D. Hardeman, 1966).

In general terms, the bedrock has a northeast to southwest trending strike with bedding that dips to the southeast. In addition, there is a southwest plunging anticline, known as the Rocky Valley anticline, located within the center



Figure 1. General location map of the SR 71 study area in Knoxville, Tenn.



Figure 2. Location of SR 71 study area in South Knoxville; Noted are Karst Area 1 and 2 and Meades Quarry Cave locations.



Figure 3. Geologic Map of the study area; Ol-Lenoir Fm.; Oh-Holston Fm.; Oo-Ottosee Fm.

of the study area and extends from near the French Broad River/Holston River confluence(the beginning of the Tennessee River) to the southwest part of Knox County. Due to the anticline structure, some strata located on the northwest limb of the structure dip to the northwest and form a limb of a small syncline, the Island Home Syncline.

The rock units are structurally oriented in a northeast to southwest position with the rock layers (bedding) dipping generally to the southeast at varying angles. Numerous fractures and other discontinuities are found throughout the strata along the study corridor and are the result of the intense folding and faulting history of the region.

Weathering has also produced knobby terrain and classic karst topography characterized by sinkholes, disappearing streams, and caves. Notable caves found in the study area include Cruze Cave and Meades Quarry Cave.

Geohazards Evaluation

Geologic hazards include such things as existing landslides or areas prone to landslides, the presence of acid producing rock, soft or weak soil, old abandoned mine sites, contaminated ground, caves and sinkhole areas (referred to collectively as karst), and earthquake prone areas.

With the exception of karst, abandoned quarry pits, and steep terrain, geologic hazards do not pose an immediate threat to the environment and public along the study corridor. The most significant hazard along the proposed corridor is karst, which is located in belts or zones that trend in a northeast-southwest direction. The karst landscape of the study corridor as well as the rest of East Tennessee is characterized by features such as sinkholes, caves and cave entrances, sinking streams and outcroppings of weathered carbonate rock (limestone and dolostone). There have been incidences of sudden sinkhole collapse as well as flooding of sinkhole basins crossed by roads or buildings. The recognition of areas of active karst subsidence and collapse is of considerable importance to the design and construction of the proposed highway.

TDOT initiated a karst geohazards inventory and assessment to assist in evaluating and selecting a satisfactory alignment within the corridor study area. This study was designed to locate caves and sinkholes within and adjacent to the proposed corridor (Figure 4).

In addition, the caves were visited and preliminarily evaluated as to their geotechnical and environmental importance. The caves that were found to be of significance to the proposed stability of the roadway or have environmental and archeological significance were surveyed to determine their lateral and vertical extent. Mapping of the caves was performed by both TDOT Geotechnical Engineering staff and local speleologists.

Caves and sinkholes offer special challenges relative to both the physical and environmental issues of highway development. The karst geohazards inventory study disclosed the presence of both sinkholes and caves, some of which may have detrimental structural, geologic, and environmental issues for the roadway alignment and grade design considerations.

A total of eight caves as well as numerous sinkholes were located within the proposed roadway corridor. Two of the caves, Cruze Cave and the Meades Quarry Cave System, were determined by the TDOT Geotechnical Section (Knoxville office) to be significant enough to require more in-depth study and analysis.

For reasons of sensitivity concerning cave conservation and landowner privacy, the cave locations are not specifically detailed in this paper; however, their names and locations are maintained in the files of the TDOT Geotechnical Engineering Section (Knoxville office) for reference when needed. Of recent note, Meades Quarry Cave (all entrances) has been gated by the Ijams Nature Center Park to control access to the cave system.



Figure 4. This sinkhole map was prepared for the geohazard study for the SR 71 project; yellow areas are sinkholes that were found based on a 20-foot contour interval.

Mapping Karst Areas within the Proposed Study Corridor

Efforts to avoid karst areas with roads and other developments are difficult at best, especially since the "good" land is already mostly developed, leaving only the geologically undesirable land for current development. Geologically undesirable land found along the proposed highway corridor includes such areas as karst terrain and steep, very rocky terrain.

In planning new highway corridors certain constraints must be known and when identified are usually displayed by mapping. The first step in a karst geohazard study is to map the surface karst features. The TDOT Geotechnical Engineering Section mapped the karst features in an effort to identify geohazard areas.

In general, 7.5 minute topographic maps (that use a 6 meter (20 foot) contour interval) were used to locate karst features such as sinkholes (closed depressions on the contour map), caves, springs, and sinking streams. Once these karst features were identified and located on the

topographic maps (Figure 4), then a field reconnaissance was performed to field check the features to make sure that they were there.

Afterwards, the sinkholes and other karst features were enhanced on the topographic maps and subjective boundaries were drawn to encircle these areas. Typically, these encircled areas are identified as "areas of high concentrations of sinkholes" and/or "areas of numerous cave openings". Actual cave entrances were not plotted on the final geohazard map due to access issues and private owner protection.

The geohazard areas were then expressed as outlined patterns on topographic maps to better illustrate the geohazard relative to the surrounding landscape. In addition, the proposed corridor route was overlain on the geohazard map. This map is then used by the roadway planners to better locate the final roadway centerline.

In some cases, maps with contour intervals as small as 0.3 to 1 meter (one to three feet) are available which

greatly enhances the sinkhole identification (Moore and McDowell, 2008). David A. Hubbard (2003) researched this issue in the karst regions of the Valley and Ridge of Virginia where he consistently identified more sinkholes on the ground than were depicted on selected 7.5 minute quadrangle maps. In one instance Hubbard described a 7.5 minute quadrangle with a 6 meter (20 foot) contour interval that revealed 55 sinkhole features, while ground field mapping identified 533 sinkhole features.

In addition to the surface mapping of sinkholes, it is becoming increasingly important to locate (step two in the geohazard study) and map the caves(step three in the study of karst geohazards) in close proximity to the proposed roadway. By knowing spatial locations of the cave passages, a more accurate design of proposed roadway cut slopes can be made. This prevents the unnecessary opening of a cave system to the surface, thus protecting the cave biota, such as bat colonies and salamanders.

The use of experienced cavers in combination with engineering survey crews provided the best results for locating the cave passages spatially with respect to the proposed roadway. It is anticipated that mapping of cave passages will become increasingly mandatory as society continues encroaching onto and into the karst environment.

After a review of available geologic data and field investigations, the SR 71 Extension corridor was found to be located within several strike belts of karst.

Numerous sinkholes and caves were found to be located in these karst areas. The most intensive sinkhole areas were mapped in order to better assess the corridor terrain (Figure 5). A field reconnaissance of the study area was made in order to locate as many sinkholes as possible. Many were overgrown and difficult to locate. A few of the caves that were identified were found to be located outside of the sinkhole zones (outlined on the attached karst-sinkhole map), but within typical karst terrain.

The possible impacts from the proposed road alignment (or any other structure, building, subdivision, etc.) on the karst environment include sinkhole collapse, sinkhole flooding, groundwater contamination and negative effects on the cave and subsurface dwelling wildlife.



Figure 5. Karst Map of study area (dashed line); blue is active/intensive sinkhole area, red is area of caves, downtown Knoxville is pink area in upper part of map.

Two major sinkhole areas were found within the proposed study corridor. These include the area just southeast of Island Home (including old abandoned marble quarries) and the Lake Forest/Moreland Heights communities. The following is a brief discussion of these two karst areas.

Karst Area 1

Karst area 1 is located in the northern part of the study area (see Figure 2) and is developed along the bedrock strike of the Holston Formation, and to a lesser extent, the Lenoir Formation. Numerous unique formations and biota, including several species of bats and salamanders, are found in many of the caves in this area.

The Holston Formation strata have been quarried as "Tennessee Marble" in the historic past, as evidenced by several old abandoned quarry pits in the Meades Quarry section off of Island Home Avenue. The quarrying operations have exposed a cave system and underground stream in several areas of the abandoned quarry pits. Five openings into the cave system were found in the old pit areas. The cave is known as Meades Quarry Cave.

Another cave in this karst area is known as "Un-named Cave", and is located next to Island Home Avenue, approximately one-half mile south of the Meades Quarry area. Entrance into the cave is very limited due to a spring that issues out of the submerged entrance. Several other large sinkholes are also found in this area, mostly to the west of Island Home Avenue.

A third cave, Cave Spring Caves, is found along the Tennessee River bluffs in what is known as Ijams Nature Park. These short double caves, approximately 24 meters (80 feet) in length), are developed in sandstone strata of the Chapman Ridge Formation. Meades Quarry Cave is also found in the Ijams Nature Park in an area to the southwest of the Tennessee River.

The karst in this area is characterized as being well developed with numerous sinkholes, open solution channels, and solution cavities located well above the zone of saturation (vadose zone). Naturally developed cave entrances tend to be in the floors of sinkholes which drain surface run-off into the vadose zone. In some instances deep soil-cover mantles the underlying bedrock which is characteristically carbonates, shale, and sandstone, are also tilted and pinnacled.

Karst Area 2 in the Lake Forest/ Moreland Heights Communities

Karst Area 2 is located near the center of the study area and encompasses the heavily populated communities of Lake Forest and Moreland Heights (see Figure 2). Numerous sinkholes are found in this area, some of which are water-filled. Three caves are located in this area and are locally known as Brown Cave, Backyard Cave, and Cruze Cave.

Two geologic formations found in this section (Holston Formation and Lenoir Formation) have karst features that are prevalent across much of the area. The area that is underlain by the Lenoir Formation tends to have relatively moderate to low relief with thin soil cover and broad sinkholes. The Holston Formation tends to underlie high ridges and hilly terrain, and produces a rich, maroon-red clay residual soil mantle. This Holston derived soil is variable in thickness, but can attain thicknesses up to 15 to 18 meters (50 to 60 feet).

Cruze Cave was visited by the author. The cave is apparently developed both in the Holston and Lenoir formations and tends to follow the dip of the bedrock as it plunges downward with the structure of the geologic anticline. The roof of the cave along with some of the upper passages were found to be developed in the Holston Formation, while the current active stream drainage conduit is developed in the Lenoir Formation.

Mapping Subsurface Karst: Meades Quarry Cave Mapping Initiative

Due to the existence of Meades Quarry Cave within the proposed study area, it was decided to map the western-most portion of the cave system. The purpose of mapping the cave was to determine if the general trend of the cave and cave stream is toward the sinkhole area around Old Sevierville Pike and Red Bud Drive, which is located within the study area of the proposed parkway extension.

The presence of the Berry Cave Salamander (*Gyrinophilus gulolineatus*, a subterranean amphibian listed as a potential threatened species – see Figure 6) in the Meades Quarry Cave stream has made the cave an important issue with respect to the proposed SR 71 extension. The Berry Cave Salamander derives its nutrition from debris and organics that are flushed into the sinkholes by rain events which in-turn recharge the

cave stream in which the salamander lives. Sinkhole modifications would directly affect the salamanders.

In August 2008 the TDOT Geotechnical Engineering Section began mapping the western-most portion of the Meades Quarry Cave system. This section has its entrance in the floor of an old quarry pit where it was exposed during quarrying operations in the 1930's and 1940's (Figure 7). Initial mapping was by the tape and compass method, but difficulties due to the thick extensive mud deposits in the cave forced us to switch to using a hypsometer.

Two mapping trips were required to gain sufficient survey data for our objective of establishing a trend for the cave passages. The mapping was performed on August 5 and August 13 of 2008.

Briefly, the cave passage consisted of a main canyontype gallery that held a flowing stream in the floor of the passage . The cave is developed in the vadose zone and is floored at the vadose/phreatic contact. Some portions of the cave contained numerous dripstone formations (speleothems), some of which were a pure white color (Figure 8). Past wastes from a lime kiln operation at the quarry may have contributed to this white character. Thick mud deposits up to 0.3 to 0.5 meters (12 to 18 inches) thick were found on the stream bed and most exposed rock surfaces.



Figure 6. This photo shows the Berry Cave Salamander (Gyrinophilus gulolineatus) as found in Meades Quarry Cave by University of Tennessee researcher Matt Niemiller (photo by Niemiller from: <u>http://www.herpetology.us/niemiller/</u>).

From our mapping effort it was determined that the cave trends in an azimuthal direction of 248 degrees (or S 58 W from the cave entrance), which is toward the numerous sinkholes found along Old Sevierville Pike. A total of 399.4 meters (1,318 feet) of cave passage was surveyed (Figure 9 and Figure 10).



Figure 7. Man-made entrance to Meades Quarry Cave.



Figure 8. Unusual white soda straw formations in Meades Quarry Cave.

Fracture type joints in the bedrock tended to form side passages through which groundwater may flow to the main stream gallery. These fracture joints were found to have two general orientations: N40 W and N35 E. The strike orientation of the bedrock (the Holston Formation) was found to be approximately North 55 degrees East.

Meades Quarry Cave is developed in a linear fashion which is sub-parallel to the strike of the bedrock and may tend to "bend" somewhat to the southwest near the upstream portions of the cave. The cave is developed in a limestone formation (Holston Formation) that forms the northwest limb of a southwest plunging anticline meaning that the bedrock is dipping to the northwest. It is interpreted that the joints which were located during the mapping program tend to dip toward the northwest as a result of being on the northwest limb of the anticline and reflects that structure orientation.

As a result of the geohazard investigation and mapping initiative, it was interpreted that the stream passage of Meades Quarry Cave does indeed lay within the study area of the proposed SR 71 extension.



Figure 9. Mapping stream cave passage in Meades Quarry Cave.

Conclusions

The result of this paper is to show how mapping karst geohazards can be effective in geotechnical studies of proposed roadways. Three main steps are involved in the karst geohazard study: (1) - map all surface karst features; (2)- locate all cave entrances; and (3)- map cave passages suspected to be impacted by the proposed roadway.

The major geohazard issue found along the proposed South Knoxville Boulevard Extension (SR 71) corridor is karst. Karst is found in numerous areas of East Tennessee, predominantly in the Valley and Ridge Province. Long linear "belts" of sinkholes, caves, sinking streams, underground stream drainage, and "dry valleys" all characterize the karst in East Tennessee. Most counties in the East Tennessee region contain some amount of karst topography.

The proposed South Knoxville Boulevard Extension (SR 71) corridor likewise, has numerous karst features that are found within the area topography. Mapping surface and subsurface karst features greatly aided the evaluation of proposed roadway corridors A result of this study was the development of a surface karst map which showed areas of numerous sinkholes, which is interpreted as areas of potential future sinkhole development.

Mapping the Meades Quarry Cave System, located adjacent to the study area of SR 71, was determined to be feasible and necessary in order to ascertain the location of the Meades Quarry Cave passages which contain the Berry Cave Salamander. As a result, a portion of Meades Quarry Cave was mapped using both conventional tape and compass survey methods and hypsometer and compass methods.

The construction of road projects, as well as industrial sites, shopping malls, and subdivisions will be problematic in karst areas and should be avoided when possible. However, if avoidance is not possible, then minimization of the impact of construction on the sinkhole and cave environments should be the objective. Such design measures as minimal cut and fill construction and minimal alterations in the surface drainage of an area (both surface and subsurface) are recommended.

Mitigation of the impacts on the karst areas needs to be included with the roadway design and construction



Figure 10. This map of Meades Quarry Cave, made by the TDOT Geotech section, shows the general stream flow direction, which is parallel to the bed rock strike direction.

plans. Proactive measures such as surface drainage filtration systems for sinkholes, impermeable lining for ditchlines (to prevent new sinkholes from forming), the use of graded rock embankments (for stability and groundwater impacts), and the use of structural bridges over sensitive sinkholes should be considered and/or employed during the roadway design phase.

Surface water run-off filtration systems have recently been constructed on a TDOT roadway project in Hamblen County, Tennessee where the run-off empties into a sinkhole. The filtration system design was based on results of a Federal Highway Administration (FHwA) Pooled Fund study that involved filtering highway run-off in karst areas. Tennessee DOT was a partner in the FHWA Pooled Fund study (Stephenson and Beck, 1995; Stephenson, et al., 1997).

The groundwater contamination issue is an important topic for this project due to the potential impact on the rare Berry Cave Salamander which lives in the Meades Quarry Cave System. Once a groundwater dye trace is completed, then a more appropriate evaluation of the karst groundwater drainage can be made.

It is important to understand that there will be an impact on the karst environment (sinkholes, caves, wildlife, and groundwater). In some places, this impact may be significant where caves and sinkholes are exhumed and/ or filled in with embankment material, and where surface drainage is directed into sinkholes that empty into the caves and groundwater systems. These impacts can be lessened by appropriate and judicious mitigation during the design and construction phase of the project.

The TDOT Geotechnical Engineering Section has already assisted the Planners and Designers in adjusting the alignment of several proposed routes and providing recommendations that minimized the impact



Figure 11. Map of SR 71 project area showing Karst Areas 1 and 2 and selected routes based on karst.

of the alignment on the known cave and karst systems (Figure 11). Projects involving karst are more costly on average than other projects, and cost overruns during construction should be anticipated due to the unknown and variable nature of karst features.

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GOVERNMENT CANYON STATE NATURAL AREA: AN EMERGING MODEL FOR KARST MANAGEMENT

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Abstract

Government Canyon State Natural Area (GCSNA) is located on the northwest edge of San Antonio, Texas, USA. Ninety percent of the 47.04 km2 property is located on the recharge zone of the karstic Edwards (Balcones Fault Zone) Aquifer. Urban development is encroaching onto the Edwards Aquifer karst and threatening groundwater quality and karst ecosystems. GCSNA has served as a model for karst management by:

- defining existing resources;
- restoring impacted resources;
- monitoring and protecting groundwater quality and quantity by encompassing 62% of the 30.46km2 Government Canyon watershed on the Edwards Aquifer recharge and contributing zones, and over 23 km2 of adjacent karst watersheds;
- preserving the unique cave fauna;
- limiting all development to non-karst areas;
- using state-of-the-art construction techniques and infrastructure to minimize water and ecological impacts;
- monitoring land use conditions for an adaptive resource management plan; and
- establishing contiguous buffers around the core resource area.

This approach was made possible by designating GCSNA as a karst preserve in order to most effectively manage all of its resources. Karst attributes of GCSNA predominantly determine the location, type, magnitude, and management of its most significant natural and cultural resources. Federally listed endangered invertebrate species and the county's largest known bat population occur in its caves. Springs and deep canyons provide habitat for a diverse flora and fauna, including the endangered Golden-cheeked warbler. These springs and species, along with chert deposits and natural trails through rugged terrain, have supported human occupation since prehistoric times. Springflow and streamflow rapidly recharge the Edwards Aquifer to

maintain this sole source system as a sustainable regional water supply. Partnerships with multiple agencies and volunteers have minimized individual costs, provided more thorough and complete assessment of karst resource issues, and developed public educational programs on the values of karst.

Introduction

Government Canyon State Natural Area (GCSNA) is located within the northwest limits of San Antonio, Texas, USA. It is a karst area that was planned for urban development but purchased by a partnership of three governmental agencies and two non-profit organizations. This arrangement was unprecedented for the state of Texas and established the first of many actions that would make GCSNA a model of how to best purchase, research, develop, and manage a property for natural resource protection. This paper first outlines the natural and cultural resources of GCSNA, then uses its history as a model example by which multi-disciplinary research and cooperation of several partners can be used for effective karst resource management.

Natural and Cultural Resources: Description and Setting

GCSNA encompasses 47.04 km2 in northwestern Bexar County at the southern edge of the Edwards Plateau. It is comprised of gently sloping karst ridge tops along its north, east, and west borders that slope steeply down to a nearly level valley floor that runs through the middle of the property. It ranges in elevation from 469 m above mean sea level near its northeast corner to 335 m where the valley's bed exits the south-central portion of the property.

The Balcones Escarpment, the topographic expression of the Balcones Fault Zone, cuts east-west across the southern edge of GCSNA. It separates the low-relief Gulf Coastal Plain from the ruggedly dissected Hill Country to the north, and marks the boundary where several geological, biological, and cultural zones meet, resulting in a high diversity of natural and cultural features.

GCSNA Geology

Three Cretaceous age limestone formations crop out at GCSNA. See Barnes (1983) for a regional geologic map. The Glen Rose Formation, the oldest unit, is found along valley floors in the northern two-thirds of GCSNA. It is approximately 165 m thick with only the uppermost 30 m exposed. The Glen Rose is a series of hard limestone and dolomite beds interbedded with softer beds of clay and marl, which erode to create a stair-step topography. Dinosaur tracks are occasionally found in the limestone beds.

Above the Glen Rose is the Edwards Limestone Group, the most cavernous unit in the study area. Rose (1972) subdivided the Edwards into the Kainer Formation at the base, with ascending Basal Nodular, Dolomitic, Kirschberg, and Grainstone members, and the Person Formation at the top, with ascending Regional Dense, Collapsed, Leached, Marine, and Cyclic members. Maclay and Small (1984) included the Basal Nodular Member as the base of the Kainer. The Edwards is a hard, crystalline, and fossiliferous rock that forms most of the steep hills and cliffs that cover the northern two-thirds of GCSNA. Nearly all of the Edwards' 137 m thickness is exposed at GCSNA (Stein and Ozuna, 1995).

The third and youngest formation exposed is the Austin Chalk. It is a relatively soft unit, approximately 60 m thick, of which about the lowermost 20 m are exposed. It underlies the flat southern third of GCSNA.

The dominant geologic feature at GCSNA is the Miocene-age Balcones Fault Zone, a system of parallel to subparallel faults that locally trend northeast to southwest and drop down to the south and southeast. With 180 m of drop, the Haby Crossing Fault has the greatest displacement of any fault known in Bexar County. Where it crosses GCSNA it is marked by the Balcones Escarpment, a sudden rise in the land where the Austin Chalk meets the Edwards Limestone Formation. South of the fault, the Edwards and Glen Rose are buried below the Austin Chalk. North of the fault, the Austin Chalk has long ago been eroded from above those units.

Groundwater in the study area occurs in or is related to one or more of three aquifers: the Edwards Outlier Aquifer, Upper Trinity Aquifer, and Edwards (Balcones Fault Zone) Aquifer (hereafter called the Edwards Aquifer). The Edwards Outlier Aquifer is the highest in elevation and informally defined here to describe groundwater that occurs in the hydrologically discontinuous, isolated outcrops of Edwards Limestone on hilltops in and near GCSNA. The aquifer is unconfined, recharges through karst features and fractures in the limestone, and locally does not yield enough water to support water wells. Some of its water flows directly into the underlying upper Glen Rose, and some is discharged from seeps and small springs near the top of the upper Glen Rose where the Edwards Limestone is perched on poorly permeable beds.

The upper member of the Glen Rose is the sole unit of the Upper Trinity Aquifer. This aquifer is unconfined and locally recharged. Although the upper Glen Rose contains enough clay and marl beds to make it the lower aquiclude for much of the Edwards Aquifer, its outcrop exposes enough limestone and dolomite beds to absorb some recharge. Regionally, there is relatively little use or demand for the aquifer's groundwater because of its low yield and its contact with gypsiferous zones, which results in occasional high sulfate concentrations. Yet locally in the north Bexar County area, most privately owned wells tap upper Glen Rose water, especially since its upper 38 m are cavernous and yield larger volumes of water. In addition to wells, the Upper Trinity Aquifer also discharges through seeps and minor springs.

Significant but poorly quantified volumes of water also discharge from the upper Glen Rose into the Edwards Aquifer. This hydrologic connection was best demonstrated in northern Bexar County through a series of dye tracing studies (Johnson et al., 2010) roughly 20 km east of GCSNA.

The Edwards Aquifer is a complex hydrologic system which is divided into four zones: contributing or drainage, recharge, artesian or confined, and saline. The contributing zone is the upgradient non-Edwards Limestone area from which streams flow onto or cross the recharge zone where water enters the Edwards Aquifer. The recharge zone is defined by the exposure of Edwards Limestone within the Balcones Fault Zone. Most of GCSNA is within the recharge zone. The artesian zone is that area where the Edwards Limestone is down-faulted into the subsurface, and its groundwater is confined between upper and lower less permeable formations. The aquifer's largest springs occur where groundwater rises up fractures to discharge in stream valleys that intersect the potentiometric surface. The "bad water line" is the downgradient boundary of the artesian zone with the saline zone, where total dissolved solids in the groundwater exceed 1,000 mg/l. Groundwater flow in western Bexar County is complicated but generally down-dip southward, then eastward along strike.

Caves and Karst

Systematic transect surveys at GCSNA have revealed 37 open caves and 360 non-cave karst features, many of which seem likely to open into caves with some excavation (Miller, 2012). Most of the caves and karst features are developed in the Edwards Limestone as recharge features for the Edwards Aquifer. Some extend into the Glen Rose Formation. A few caves are phreatically formed and predate the modern aquifer, most notably Government Canyon Bat Cave which is the largest cave chamber in the county at about 90 m long by 20 m wide by 8 m high. While the Austin Chalk is cavernous elsewhere in Bexar County, no caves or notable karst features occur at GCSNA probably because the outcropping horizon is less permeable and soluble.

Caves at GCSNA are typically small and relatively shallow. Dancing Rattler Cave is the longest at 225 m and Lost Pothole the deepest at 23 m. Similarly, sinkholes are small, typically <2 m in diameter and <0.3 m deep. Sinkholes are rare in the upper Glen Rose, especially solutionally-formed sinkholes, but one significant sinkhole collapse occurred within the unit following rainfall in Spring 2011. At 5 m by 3 m by 8 m deep, Turquoise Sink is the largest collapsed sinkhole in the county to occur in historic times.

While the karst features of GCSNA are topographically subdued, their collective karstic permeability is high. The Government Canyon stream bed is normally dry except where perched for short distances immediately downstream of springs. A few sections of the valley floor gently rise in the downstream direction as they pass areas of high fracture permeability. Monitoring of flows (unpublished data) show only water from the largest storm events flows off the Edward Aquifer recharge zone via that stream bed without being fully diverted into the aquifer.

GCSNA Cave and Karst Biology

The epigean fauna of GCSNA includes a diverse array of mammals, herpetofauna, and invertebrates. Birds are especially abundant with over 90 species identified, including the federally listed endangered Goldencheeked warbler and Black-capped vireo, that latter of which was first reported in 1972 but is seldom seen (Wiesema, 1972). This diversity is a direct result of Government Canyon's sheltered to open environment, its location at the junction of two major ecological zones, and especially due to the presence of perennial karst springs, which are not found in many other canyons and valleys along the Balcones Escarpment.

GCSNA's hypogean fauna is arguably more significant and proportionally diverse. Cave ecosystems, by their nature as food-poor environments, have lower species populations and diversity compared to surface ecosystems. But relative to many karst areas, the caves and karst features of GCSNA are biologically rich with 65 identified species, 15 of which are troglobites, 14 troglophiles, and at least an additional 53 species remaining to be identified. Of the troglobites, six invertebrates are federally listed as endangered species, occurring in 14 GCSNA caves, and one is endemic to GCSNA. While not endangered, three bat species are known in at least seven caves, with Government Canyon Bat Cave containing the largest bat colony in the county (Miller and Reddell, 2011).

Cave and Karst Cultural Resources

For thousands of years, Government Canyon has been an important natural thoroughfare through the rugged hills along the Balcones Escarpment in the San Antonio area. Unlike most canyons in the region that end steeply, Government Canyon maintains a gentle gradient from the base of the escarpment up to the fringe of the Edwards Plateau. Indians, Spaniards, US military, and ranchers used the canyon's natural trail, spring-fed water, wild game, and vegetation.

A number of archeological sites have been recorded in GCSNA (Dillehay, 1972). Most of these sites represent Native American encampments, one roughly estimated as representing several thousand years of regular occupation; 24 sites are eligible as State Archeological Landmarks. McNatt et al. (2000) provided an evaluation of prehistoric use of its southernmost area, and Greaves (2002) examined archeological features near parts of GCSNA's trail system, but a comprehensive archeological study of the entire property is needed in order to definitively determine the full extent to which Government Canyon was used by Native Americans and the nature of that use. Doubtless it served as a vital and reliable source of water, as well as for chert for

tool-making, since chert is only found in the Edwards Limestone in the region. At least two caves are known to have served as human burial sites (Veni, 1994 and 1996). Also within the Natural Area is a historic structure, believed to have been built in 1883, referred to as the Zizelmann House. This stone and wood structure purportedly has seen use as a home, a stage coach stop, and in later years, a hunters' camp.

GCSNA: A Model for Karst Management Partnerships for Land Acquisition and Protection

In the 1850s, Government Canyon became an important route between San Antonio and military forts to the northwest. This use by government troops gave the canyon its name. In the 1880s, it became a busy stage coach route between the towns of San Antonio and Bandera, and along with surrounding areas, most of the canyon began to be consolidated under the ownership of the Hoffman family. The Hoffmans and their successors ranched the property for about 100 years.

In the 1970s, the San Antonio Ranch New Town Corporation purchased the ranch to build a community with a proposed population of more than 80,000 residents. They continued to lease most of the property for ranching but only developed the northeast corner along Highway 16. In the late 1980s, the corporation failed during the nationwide savings and loans collapse, and the property was taken over by the federal government's Resolution Trust Corporation (RTC).

RTC placed the property for auction, where it was nearly purchased again for development. However, it was saved through the action of the Government Canyon Coalition (GCC), a group of 45 civic and environmental organizations. The Government Canyon property encompassed much of the Government Canyon watershed over the karstic Edwards Aquifer recharge zone, the primary water supply for the region. Growth of the City of San Antonio onto the recharge zone had raised concerns about preserving the aquifer's quality and quantity (e.g. Kipp et al., 1993) and owning key portions of the recharge zone was seen by the GCC as an effective means of aquifer protection.

The GCC first sought to have the property purchased by the Texas Parks and Wildlife Department (TPWD), which

lacked the funds. The City of San Antonio and Edwards Underwater Water District (EUWD; now reorganized as the Edwards Aquifer Authority) were approached, but the city did not see the value in owning parts of the recharge zone while EUWD saw the value but did not want to own and manage land. This impasse was breached when the GCC involved the Trust for Public Land (TPL). TPL got Government Canyon removed from the auction list and facilitated a deal for its purchase by TPWD. Since TPWD was short of funds, TPL and GCC convinced the City of San Antonio's San Antonio Water System and the EUWD to pay 75% (\$1.5 million) of the purchase price, while TPWD maintained title and general management of the 19.09 km2 property. The property was designated as Government Canyon State Natural Area. See Freeman (1994) for a detailed history of the property up to the time of this acquisition.

The establishment of GCSNA served as a magnet to expand protection of the Government Canyon karst watershed, but also for the protection of its other natural and cultural assets. Figure 1 illustrates the acquisitions of properties surrounding the initial purchase as described in the following narrative.

On November 3, 1994, the US Department of Housing and Urban Development committed to adding 4.54 km2 to the property's northeast corner and was deeded to TPWD 15 months later. This tract was also part of San Antonio Ranch, but the presence of the endangered Golden-cheeked Warbler and the rugged terrain severely limited its capacity for development. TPWD made it a sanctuary for the Warbler, with no public access into that area during the months the birds are nesting.

The next acquisition occurred in 1999 through TPL which transferred ownership to TPWD of the 3.26-km2 Davis Ranch—Upland Tract due to \$1,581,000 in donations from the San Antonio Water System and the Duncan, Frost, Kronkosky, Meadows, Morris Stafford, and USAA charitable foundations and trusts. The next year, TPL arranged the transfer of the 1.60-km2 Gallagher Ranch to TPWD via additional independent fundraising efforts which covered all but \$500,000 of the total contract price, which TPWD paid with general operating funds. In 2002, TPWD purchased the 4.70-km2 Kallison Ranch from TPL for approximately \$5 million and sold a conservation easement to the City of San Antonio. TPWD used the funds from the city to



Figure 1. Properties acquired to expand GCSNA and protect the karstic Edwards Aquifer.

qualify for a Land and Water Conservation Fund grant which covered 58% of the purchase price.

This creative and cooperative development of funding was instrumental in heightening public awareness of the importance of GCSNA in protecting the Edwards Aquifer and its endangered species. So starting in 2001, San Antonio citizens passed the first of three sales tax increases that in total raised \$220 million to buy land to protect the Edwards Aquifer recharge zone and endangered species, and allow for limited recreation. By 2009, this tax initiative led to the purchase of four additional properties adjacent to GCSNA that totaled 12.14 km2. They are all in the process of being deeded to TPWD for management. During this time the 1.70 km2 Ma-Be Canyon was purchased and Ruth McCrary donated a small but environmentally important 0.01 km2 for similar aquifer and species protection. These acquisitions raised the total contiguous area of GCSNA (including two on the opposite side of Texas Highway 211) from an initial 19.09 km2 to 47.04 km2, extending into neighboring Medina County, and protecting more than 41 km2 of the Edwards Aquifer recharge zone and its endangered species habitat, and about 62% of the Government Canyon watershed on the Edwards Aquifer recharge and contributing zones (Figure 2).

Partnerships for Multidisciplinary Karst Management

GCSNA was slow to open to the public. The core section of the property was acquired in 1993 but it was not opened to the general public until October 2005. The delay was not due to insufficient funding but from the TPWD mandate that the primary purpose of a "State Natural Area" is resource protection and management, with recreation being of secondary importance and must not adversely impact the natural area's resources. Therefore, before recreation and public access was possible, TPWD conducted inventories of its natural and cultural resources to determine the important scenic, educational, hazardous, and sensitive areas of the property. Surveys include studies of caves, plants, animals, history, and pre-history. Where possible, volunteers were used, and continue to be used to conduct



Figure 2. GCSNA boundaries and the Government Canyon drainage area relative to the Edwards Aquifer contributing, recharge, and transition zones.

or assist with these surveys. The Government Canyon Karst Project alone has conducted 110 trips from August 1994 through October 2012 to survey, study, and restore or protect, where needed, GCSNA's cave and karst resources (Miller, 2012).

The focus for much of the resource work, especially before GCSNA opened publically, was through the Government Canyon Natural History Association (GCNHA). In 1995, GCC reorganized itself into GCNHA, a nonprofit corporation dedicated to organizing and managing support for the Natural Area. On November 15, 1996, a Memorandum of Agreement (MOA) between TPWD and GCNHA established a framework to cooperatively promote the preservation and protection of the natural and cultural resources of the natural area. Toward this end, GCNHA assisted TPWD in:

- 1. developing a management plan to ensure the protection and appropriate use of GCSNA;
- 2. working to preserve and protect the natural and cultural resources of GCSNA;
- developing educational programs on the natural and cultural resources of GCSNA for the visiting public;
- building a constituency of support for GCSNA; and
- 5. promoting volunteerism for GCSNA.

After GCSNA's public opening, GCNHA changed its name to the Friends of Government Canyon and as of October 2012 has logged over 200,000 volunteer hours in resource study, protection, management, and public education programs (Friends of Government Canyon, 2012).

In 1998, the Government Canyon Master Plan (TPWD, 1998) was adopted. It emphasized protection of the Edwards Aquifer, as well as the natural area's endangered and threatened species and cultural resources. Dictated by principle and enforced by deed restrictions, all development and new park facilities would be restricted to the southernmost sections that are off the Edward Aquifer recharge zone. The majority of GCSNA, which is over the recharge zone, currently has almost 68 km of multi-use trails; a few dirt roads are present only for emergencies, natural area maintenance, and research. These trails are only within the initially-

purchased 19.09 km2 and the 4.54-km2 Housing and Urban Development-acquired tract. Study of the more recently acquired properties is underway and their use will be determined accordingly when their resources are better identified and understood.

Most cave and karst research and management activity at GCSNA is unpublished, limited primarily to reports submitted to TPWD. The majority is through the Government Canyon Karst Project, but other works include stream flow and recharge monitoring by the US Geological Survey, as well as student and other independent research.

The most active karst management activity involves monitoring the populations of the endangered karst invertebrates and active management actions such as regular eradication of the non-native Red Imported Fire Ants (Solenopsis invicta) which predate upon the karst species. As a result of TPWD's proactive efforts through its Karst Management and Maintenance Plan and assistance by its volunteer partners, the US Fish and Wildlife Service determined that "management for the caves and the species in the Natural Area provides adequate special management considerations for the primary constituent elements, and consequently [habitat] units within the Natural Area that we proposed for [critical habitat] designation are not included" (USFWS, 2003). This determination provided GCSNA fewer constraints in its research and management activities, and may lead to continued support for future karst projects.

Conclusions

Government Canyon State Natural Area is a model for the protection and management of specific caves and karst areas through partnerships and creative financing for property acquisition, deed restriction, public education and tax-payer initiatives, and multidisciplinary research and management actions. The synergistic karst-related benefits are the protection of the quality and the quantity of recharge into the karstic Edwards Aquifer, the primary water supply for nearly 2 million people, and the simultaneous protection of habitat for six endangered karst species. Habitat protection for an endangered bird species that nests mostly in karstic canyons and easy access to a large natural karst environment which educates the citizens of Texas about karst are additional major benefits. Cultural resources, while rarely found in GCSNA caves, are generally not discussed publicly until funds can be allocated for their proper study and management.

GCSNA staff and volunteers understand the importance of karst and highlight it in their public education efforts. The GCSNA gift shop is named "Recharge" to stress the property's value to spiritual, ecological, and aquifer replenishment. And the attitude at GCSNA of waiting to understand their complicated resources and their complex relationships, before deciding how to manage them, should be applauded and followed in all karst areas.

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COMBINING LIDAR, AERIAL PHOTOGRAPHY, AND PICTOMETRY[®] TOOLS FOR KARST FEATURES DATABASE MANAGEMENT

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Abstract

The mapping of karst features has taken on increasing importance in land use planning and zoning regulations across south east and east central Minnesota. The delineation of sinkholes, springs, and other features has traditionally depended on extensive field work, using topographic maps, and intensive networking with local landowners. The luck of the observer has also been critical as many sinkholes are rapidly refilled by landowners, concealed within extensive row crops, or hidden under tree canopies.

The application of aerial tools allows mapping across large areas. Potential karst features can be identified, and indistinct or otherwise suspicious points targeted for field verification. LiDAR mapping across Minnesota now allows high-resolution imaging (1.5 m horizontal and <15 cm vertical) of small depressions in karst landscapes without interference from vegetation. These features can be visually compared to aerial photography, both visible and infrared, flown periodically by the U.S. Department of Agriculture (USDA) to verify persistence and/or reappearance of features through time. Additionally, low angle, highresolution Pictometry® imagery allows overhead views from several angles to further identify and verify the genesis of a given depression. In areas with previously mapped karst features, precise locations can be compared to earlier estimates of location, which is particularly useful in applications like nearest neighbor analysis.

The improved elevation mapping resulting from LiDAR work has greatly improved geologic mapping efforts based on well driller's logs. This improvement in geologic mapping allows much better correlation of karst features within stratigraphic units as well as identifying structural controls. The geologic mapping efforts are beyond the scope of this paper.

While field verification is the ultimate standard, many obvious sinkholes can be identified, and numerous nonsinkhole depressions eliminated from consideration, helping focus valuable field time.

Introduction

There are many different types of karst features found across soluble bedrock terrains. Caves and springs represent some of the most spectacular karst features. Sinkholes on the other hand, while generally more numerous, are much more ephemeral. The appearance of a sinkhole, or its recurrence, is often inconvenient and occasionally catastrophic. Ford and Williams (2007) suggest that sinkholes are a "diagnostic" feature of karst landscapes. One pundit is quoted as saying that "the best predictors of new sinkholes are existing sinkholes" (Alexander and Lively, 1995). The mapping of sinkholes is therefore one of the primary tools in the delineation of, and assessment of risk on, karst terrains.

Mapping the distribution, size, and shape of sinkholes has always been a labor intensive effort. Extensive field work to locate points on topographic maps was combined with hours of reviewing aerial photographs into a database for further analysis (Gao et al., 2005a,b and Gao et al., 2006). Several new tools are becoming rapidly available that fundamentally change our approach to discerning, locating, and delineating sinkholes across counties and whole states.

Chief among these new tools is LiDAR (Light Detection And Ranging). The hillshade LiDAR image, Figure 1, of several large sinkhole complexes illustrates how clearly these features appear (note 3 smaller sinkholes



Figure 1. LiDAR imagery of large sinkholes east of Utica, Minnesota, with white circle highlighting sinkholes.

in the upper left). All of these large depressions show up on conventional U.S. Geological Survey (USGS) 1:24,000 topological maps. The karst of southeastern Minnesota is typified by these suffosion sinkholes where a thin veneer (less than 15 m) of glacio-fluvial sediments covers Ordovician carbonates. These depressions can be approximated as a series of intersecting conical sections as expected by subsurface sediment transport.

Airborne LiDAR is used to create Digital Elevation Models (DEMs) and Digital Terrain Models (DTMs). These models can be combined with other geographically referenced maps and photos within a Geographical Information System (GIS) allowing the mapping of landscape features. In particular, bedrock geology, surficial sediments, depth to bedrock, and soils can put sinkholes into a geologic context.

A distinct advantage of LiDAR is its ability to "see" through vegetation mapping the land surface. This is an improvement over traditional aerial photography especially in densely wooded areas and areas with extensive agricultural cropping. Figure 2 is a conventional air photo taken in the fall, after the leaves have fallen of the trees. Even with the leaf cover off there are no obvious sinkholes, in stark comparison to the numerous sinkholes visible in the Figure 3 LiDAR image (note that Figures 2 and 3 are at the same scale, but of a different area, as Figure 1).

While traditional aerial photography looks straight down Pictometry[®] methods are now capturing low altitude, high-resolution views from multiple angles. Pictometry[®] imagery can capture easily interpretable photos across county scale projects.

In Minnesota LiDAR mapping has been driven by the delineation of flood zones, following an August 2007 event that produced 10 inches of rain across much of southeastern Minnesota (Loesch, 2009). This has been followed up by a statewide effort, the Minnesota Elevation Mapping Project (2012), funded by the state legislature as part of the Clean Water Land and Legacy Amendment to the State Constitution. Mapping is being done at 1.5 meter horizontal spacing with 15 centimeter vertical accuracy.

In addition to improvements in DEMs due to LiDAR, similar improvements have been occurring with aerial photography. Web Map Services (WMS) compile data that can be displayed in a GIS environment without having



Figure 2. Color air photo of woodlot west of Utica, MN (Fall 2011).



Figure 3. LiDAR imagery of sinkholes in Figure 2 woodlot area.

to download all the data. The Minnesota Geospatial Information Office compiles aerial photography from numerous state and federal agencies into one easily accessible location. This data includes visible spectrum aerial photography going back to 1991 along with color infrared and Landsat imagery (MNGeo's Clearinghouse Data Catalog, 2012).

Stepping beyond traditional aerial photography, where the observer is looking straight down from high altitude, oblique imaging methods are becoming much more widely available (Kalinski, 2010). Oblique imaging, commonly referred to as pictometry, is a patented imaging process that collects images looking downward at a 40 degree angle from low altitude aircraft (Pictometry International Corporation, 2002). Typical coverage includes 12 to 20 overlapping images collected from several directions for any given point on the landscape. As pictometric images provide a bird's eye view similar to what you would see from a tall structure or mountain side, features are more intuitively interpretable and understandable.

Traditional aerial photography provides an important historical record. The USDA has flown large areas of the U.S. about every ten years since the 1930s. A US Geological Survey Digital Ortho Quadrangle (DOQ) taken in 1991, Figure 4, is readily available from Google Earth [www.google.com/earth/index.html].

Methods

The section of land in Figures 4, 5, and 6 contains downtown Utica, Minnesota in the northwest corner of the images. In this photo a newly installed, at that time, tile line is visible crossing from the lower left to the top center of the image. In addition, two sinkholes mapped by prior field work are denoted. These sinkholes (D010 and D295) occur in the top of the Prairie du Chien Limestone.

There are several other features of note in Figure 4. First, there is a remnant band of St. Peter Sandstone lying on top of the Prairie du Chien, appearing as a light colored soil north and east of the D295 label. Note that the soils in this area are relatively thin, less than 0.5 meter thick over the St. Peter rises, and up to one meter thick over the Prairie du Chien. Second, there are darker colored soils associated with the tile lines, especially along the east-west section at the top of Figure 4. The darker colors

are indicative of soils that are holding moisture, i.e. are thicker than in adjacent areas, with up to 3 to 5 meters of soil. Lastly, there is a light colored area (labeled) that is difficult to tell if it is a positive or negative feature. Given the relatively flat topography of the area, a topographic map does little to help discern whether this is a small rise or if it is a depression.

Figure 5 is a hill shade image of LiDAR data for the Figure 4 area. The hill shade image highlights topographic features by illuminating the LiDAR data with an artificial light source, in this case from the northwest. The tile lines now appear as trenches in this shaded relief image and the St. Peter mounds stand up from the surrounding landscape. A small mesa capped by the Platteville Limestone over St. Peter Sandstone is visible in the southwest corner. More subtle are several fence lines that now show up as positive features providing evidence of soil erosion in the agricultural fields.



Figure 4. Google Earth image Utica, Minnesota area April 1991.



Figure 5. Hillshade LiDAR image of Figure 4 area.



Figure 6. Pictometry[®] image of Figure 4 area.

A series of depressions in the top center of the figure can now be mapped as suspected sinkholes and are indicated by numbered red diamonds. Previously mapped sinkholes are denoted by red "x"s. Note that the light colored area from Figure 4 is now an obvious depression. Interestingly the tile line jogs around this depression, suggesting that it can seasonally hold water diverting construction of the tile line.

Figure 6 shows a Pictometry[®] image covering most of the same area as in Figures 4 and 5. This image is from 2010 and shows a landscape concurrent with Figure 5. This image is available from Bing[™] Maps [www.bing.com/maps/]_using the "Birds eye" view feature. The more native, or natural view, allows further interpretation of the landscape imagery.

Efforts at conservation, in particular the Conservation Reserve Program (CRP) are visible in Figure 6. The creation of berms around sinkholes and permanent vegetation help reduce direct run-in to sinkholes and allow for filtration of water as it passes into the subsurface.

As shown in Figures 4, 5, and 6, each aerial imaging method has advantages that can be used in a complimentary fashion. Used together these tools allow complete access across county-wide scales at spatial and temporal scales that were not previously available. Additionally, bedrock geologic maps and surficial sediment thickness maps can aid in the identification of sinkhole prone areas and the distribution of mapped sinkholes can be fed back into geologic maps.

Discussion

The imagery methods described so far do a good job of identifying depressions in the landscape. There are, however, assorted depressions on the landscape that are not sinkholes; simply identifying depressions will not create a sinkhole inventory. Separating and identifying sinkholes from numerous non-karstic depressions requires an accounting of these other types of depressions. This is particularly important in glacially and fluvially altered land surfaces as are common across Minnesota.

Common non-karstic depression features include old building foundations as in Figure 7. Distinguishing characteristics are the relatively rectangular shape and its proximity to an existing farm yard. The combination of pictometry, allowing us to see the farmyard and wood lot, with the shape of the depression from LiDAR allows a definitive explanation of the observed feature. A related type of feature would be small quarry pits that were dug to extract building stone for these same barn foundations. Quarries however are usually open on one end to allow for wheeled transport.

A second type of agriculturally derived depression is the cattle wallow. Cattle, and their bison predecessors on this landscape, are known to wallow in mud to help ward off flies. These wallows can become quite deep over time.

Figure 8 shows a Pictometry[®] image of a wood lot grazed by cattle which includes a sinkhole and a cattle wallow. The sinkhole in the LiDAR inset of Figure 8 is a visible depression. The cattle and their associated wallow can be seen on the right side of the image. The slight ridge in the lower center of the image is a high traffic area that may provide a breeze to help further ward off the flies.

These cattle wallows, and especially bison wallows, can be quite large in size and depth. Figure 9 shows an early 20th century image from Kansas as reported by Darton in a USGS Folio (1920).

Another distinct type of non-karst depression is the tree tip-up or windthrow. Depending on the tree size, species, and soil depth, tip-ups can be significant features up to 3 to 4 meters across and more than a meter deep (José Ramón et al., 2000). Figure 10 shows a typical tree tipup, in this case in a maple forest. A notable feature of tip-ups is that while creating an often circular depression they always create an associated mound where the root ball lands. These mounds and tip-up depression pairs can persist for decades.



Figure 7. Former barn foundation.



Figure 8. Sinkhole D904 in woodlot with nearby cattle wallow.



Figure 9. Buffalo wallow, shallow circular depression in the level surface (from Darton, 1920).

Figure 11 shows a LiDAR image of a maple and oak forest on the Kettle River plain in Pine County, Minnesota. This is an area of thin soils over sandstone bedrock. Note that there is a distinct size to these tip-up depressions. In particular, there is a definite size range where only the largest trees are vulnerable. While sinkholes are common in the area, sinkholes do not seem to form at this elevation. The low hydraulic gradient to the base level in the Kettle River of the area shown in Figure 11 is apparently not conducive to sinkhole formation. In Minnesota, where most of the state has been recently glaciated, there are numerous depressions formed due glacial processes and particularly due to ice block melting processes. The most recent glaciation however missed southeastern Minnesota passing to the west forming Des Moines Lobe tills. Areas overlain by Des Moines Lobe tills generally have more than 15 meters of unconsolidated sediment over bedrock. The surface expression of karst in these areas is limited (Alexander and Lively, 1995).

In areas where the depth to bedrock is less than 15 meters there may be a mixture of karst, non-karstic, and hybrid depressions on the landscape. Glacial and karst features can become intermixed and examples of composite features are known in Minnesota (Shade, 2002). In portions of Pine County Minnesota, along the Kettle River, the mixture of karst and non-karst features is common (Figure 12). The Kettle River valley is incised into the Hinckley Sandstone creating large hydraulic gradients. Sinkholes in this area are the result of dissolution of the highly cemented quartz sandstone and solutional enlargement along pre-existing fractures. In Figures 12 and 13 white circles highlight sinkhole



Figure 10. Tree tip-up. Photo by Kerry D. Woods.



Figure 11. Array of tree tip-ups from Kettle River plain, Pine County, MN.



Figure 12. Sinkholes in sandstone karst above Kettle River.



Figure 13. 2010 aerial photo of Figure 12 area.

depressions and black circles denote tree tip-ups. In addition there are numerous wetland depressions of various sizes. The wetland areas are more obvious in the aerial photography image of Figure 13.

The wetlands in Figures 12 and 13 are likely kettle depressions, or ice block melt out features related to retreat of the Superior Lobe ice sheet (Shade et al., 2002). As the surficial sediments thin towards the river bluff more sinkholes begin to appear. Several of the sinkholes in Figures 12 and 13 appear to be limiting the water levels in adjacent wetlands. The wetland depressions may eventually be entirely captured by the sinkholes.

A final type of non-karstic depression, presented in this paper, is the land slide or slump. Figure 14 shows a hill shade LiDAR image of the edge of a Platteville mesa immediately to the west of Utica, Minnesota. The Platteville Limestone provides a cap to the mesa while the steep side slopes are St. Peter Sandstone. Water is transported horizontally along bedding planes in the Platteville. Seeps form across the St. Peter slope creating frequent slumps. Potential sinkhole features, that have a different morphology from the slumps, are highlighted with red and blue circles.

Figure 15 is the same area from Figure 14 but the Pictometry[®] image shows slumps in the St. Peter slope where the white sandstone is exposed. The washout from the slumps frequently extends out into the farm fields below. The four potential sinkholes are obscured by the wooded slope.



Figure 14. LiDAR image of slumps and potential sinkholes (circles) west of Utica, MN.

Figure 16 shows the same area as in Figures 14 and 15 but now presents the view looking southward, or up slope. The two blue circles can now be defined as depressions into the surface at the base of the bluff without light colored wash out fans; they are therefore not slump features. These two features may be sinkholes into the underlying Prairie du Chien. The two red circled areas are still hidden within the forested slope.

Field investigations were required to definitively identify the suspected karst sinkholes. There are occasional sinkholes near the edge of the Platteville into the St. Peter as seen in the southernmost red circle. These Platteville sinkholes, particularly near bluff edges, can be the result of mechanical erosion of the poorly cemented St. Peter Sandstone along bedrock fractures (Barr and Alexander, 2009). The second red circle is a sinkhole into a St. Peter crevice. The two blue circles, based on the visual and elevation data, are likely sinkholes into the Prairie du Chien. Definitive confirmation would likely require excavation as demonstrated by Shade (2002).



Figure 15. Pictometry[®] view looking to the north of slumps and potential sinkholes in Figure 14.



Figure 16. Pictometry[®] view looking to the south of slumps and potential sinkholes in Figure 14.

Results

Over the past three years summer interns, funded by the NSF-REU program, have actively mapped sinkholes. Originally, efforts used just LiDAR but are increasingly employing aerial and Pictometry[®] photos. Efforts to date have been aimed at southeastern Minnesota. In addition, mapping has been supported by the Water Resources Center at the University of Minnesota (see Ramini and Alexander in these proceedings). The results of these mapping efforts are in the process being added to the Karst Features Database for Minnesota (Gao et al., 2006).

In Houston County, in the far southeastern tip of Minnesota, the number of mapped sinkholes increased from 5 to 44 after mapping in 2010 by Erik Larson. This was the first county-scale application of LiDAR based sinkhole mapping in Minnesota. A significant amount of field time was required to distinguish sinkholes from non-karst depressions. The results of these efforts can be seen in the large discussion section of this paper.

Fillmore County required a more significant effort. As part of the Fillmore County Geologic Atlas (Witthuhn and Alexander, 1995) a total of 6,199 sinkholes were mapped primarily with extensive field work using 1:24,000 USGS topographic maps as a base. In 2011, Britney Greenwaldt and Cody Bomberger mapped an additional 4,431 sinkholes in Fillmore County. They were able to confirm the location of 3,504 previously mapped sinkholes. They adjusted the location of 1,542 previously mapped sinkholes with an average correction of less than 15 meters. A significant portion of the 2,695 sinkholes that were not visible in LiDAR had been mapped through discussions with landowners and county soil conservation officers to locate filled sinkholes.

Previous mapping in Winona County had identified 672 sinkholes. Work by Rahimi and Alexander, presented in these proceedings, identified an additional 651 new potential sinkholes and refined the location of 168 sinkholes.

Work is on-going with renewed mapping efforts for Wabasha, Dodge, Steele, and Washington counties of Minnesota. The Karst Features Database, as managed by the Minnesota Department of Natural Resources, is now being used by county and state officials to help direct land use decisions. A thorough and accurate database of sinkholes, and other karst features, is helping inform the siting large scale animal operations and municipal waste water facilities, along with many other intense types of land use.

Conclusions

Modern imaging and elevation tools can provide a wealth of information. Individually, aerial photography, pictometry, and LiDAR can significantly aid efforts to map many different types of features. Used in combination these methods can significantly reduce the time required for field mapping.

Where these new GIS coverages have been applied in Minnesota the number of mapped sinkholes has been roughly doubled. In addition, the locations of previously mapped sinkholes in these areas have been refined. Future efforts analyzing the distribution of karst features, such as with nearest neighbor analysis, will be more robust and meaningful.

None of these methods will eliminate the need for fieldwork. They do however allow investigation of areas that were previously inaccessible and allow mapping at scales that would require thousands of hours of field effort. The mapping of features using historic air photos to identify features that have been filled is beginning.

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AN EVALUATION OF AUTOMATED GIS TOOLS FOR DELINEATING KARST SINKHOLES AND CLOSED DEPRESSIONS FROM 1-METER LIDAR-DERIVED DIGITAL ELEVATION DATA

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Abstract

LiDAR (Light Detection and Ranging) surveys of karst terrains provide high-resolution digital elevation models (DEMs) that are particularly useful for mapping sinkholes. In this study, we used automated processing tools within ArcGIS (v. 10.0) operating on a 1.0 m resolution LiDAR DEM in order to delineate sinkholes and closed depressions in the Boyce 7.5 minute quadrangle located in the northern Shenandoah Valley of Virginia. The results derived from the use of the automated tools were then compared with depressions manually delineated by a geologist. Manual delineation of closed depressions was conducted using a combination of 1.0 m DEM hillshade, slopeshade, aerial imagery, and Topographic Position Index (TPI) rasters. The most effective means of visualizing depressions in the GIS was using an overlay of the partially transparent TPI raster atop the slopeshade raster at 1.0 m resolution. Manually identified depressions were subsequently checked using aerial imagery to screen for false positives, and targeted ground-truthing was undertaken in the field. The automated tools that were utilized include the routines in ArcHydro Tools (v. 2.0) for prescreening, evaluating, and selecting sinks and depressions as well as thresholding, grouping, and assessing depressions from the TPI raster. Results showed that the automated delineation of sinks and depressions within the ArcHydro tools was highly dependent upon pre-conditioning of the DEM to produce "hydrologically correct" surface flow routes. Using stream vectors obtained from the National Hydrologic Dataset alone to condition the flow routing was not sufficient to produce a suitable drainage network, and numerous artificial depressions were generated where roads, railways, or other manmade structures acted as flow barriers in the elevation model. Additional conditioning of the DEM with drainage paths across these barriers was required prior to automated

delineation of sinks and depressions. In regions where the DEM had been properly conditioned, the tools for automated delineation performed reasonably well as compared to the manually delineated depressions, but generally overestimated the number of depressions thus necessitating manual filtering of the final results. Results from the TPI thresholding analysis were not dependent on DEM pre-conditioning, but the ability to extract meaningful depressions depended on careful assessment of analysis scale and TPI thresholding.

Introduction

Airborne LiDAR (Light Detection and Ranging) offers enormous potential for mapping sinkholes. However, techniques and approaches for using LiDAR to map sinkholes or other types of depressions have not been standardized. In the past, contour maps or digital elevation models were visually inspected for the presence of closed depressions, and these depressions were identified or manually digitized within a Geographic Information System (GIS) (Angel, 2004; Seale et al. 2008). Visual interpretation and delineation of depression features is painstaking, subjective work. Therefore, datasets of sinkholes and other karst features mapped from GIS data may not be comparable among different interpreters or regions studied. Moreover, complete field verification of individual features is often impractical, thus the reliability of manually digitized sinkhole data produced by even a singular worker may be questionable. Other studies which have examined the use of digital data (including contours derived from LiDAR) for manual interpretation of karst features have shown that subjectivity in the methodology can result in false positive and false negative identification of karst features (e.g., Seale et al., 2008; Vacher et al., 2008).

The goal of this study was to compare manual interpretation to automated detection of sinkholes and other depressions using raster GIS-based methods and a 1m resolution LiDAR-derived 'bare-earth' digital elevation dataset. Two approaches of automated depression detection were utilized. The first approach employed GIS reconditioning of the LiDAR DEM for watershed analysis (e.g. ArcHydro tools). Typically, reconditioning is done as a first step to watershed analysis to find and fill areas of closed depressions to their hydrologic spill point in order to correctly model surface flow patterns. Many depressions on coarse-scale DEMs are artifacts of the DEM production process and sink filling removes these errors (Maidment, 2002). However, these depressions are more likely to be actual geomorphic features in areas of karst terrain and on highly accurate LiDAR -derived DEMs (Zandenberg, 2010; Lindsay and Creed, 2006). By subtracting the original elevation data from the resulting filled elevation model, a new difference grid elevation dataset is produced representative of depression location and depths (Anders et al., 2011; Siart et al., 2009; Antonic et al., 2001).

The second approach used the Topographic Position Index (TPI), a GIS moving window operation that calculates the difference between the elevation at each pixel in the DEM and the mean elevation in a neighborhood surrounding the pixel (Jenness et al. 2011). The TPI is similar in concept to other local topographic relief measures that can be calculated in GIS such as the Terrain Shape Index proposed by McNab (1989) and the difference in mean elevation moving window operator proposed by Gallant and Wilson (2000). Different feature scales can be assessed by varying the size of the analysis window, and various feature types can be assessed by using square, triangular, circular, or annular window shapes. The resulting GIS dataset quantifies the landscape position of each pixel as being either higher or lower than a localized average (Jenness et al., 2011). Negative TPI values represent topographic lows (concavities, depressions), while positive TPI values represent topographic highs (convexities, ridges). The TPI (or similar concepts) has been used recently to find smallscale, concave (e.g., cave) openings (Weishampel et al., 2011), and convex burial mounds (De Reu et al., 2011), and thresholding the TPI values has been suggested as a means of classifying depressional features on the landscape (Klingseisen et al., 2008).

For this study, no effort was made to distinguish among sinkholes and other types of depressions, whether natural or manmade. The goal was simply to test the reliability of automated techniques for finding depressions in a LiDAR elevation model against a manually produced dataset within a GIS. Further work to build a karst feature dataset of the area will focus on separating true karst features from manmade features, and sinkholes from other types of natural depressions such as ponded springs, estavelles, or suffosion depressions.

Study Area

The study area is the northern half of the Boyce 7.5 minute quadrangle in Clarke County, Virginia, a region of approximately 70 km² (Figure 1). The Boyce quadrangle is located within the Shenandoah River drainage basin, an extensive karst region within the Great Valley physiographic province of the Appalachian mountain range. The geology of the quadrangle was originally mapped by Edmundson and Nunan (1973); however, an inventory of karst features was not included in the original mapping. Hubbard (1983) identified a small



Figure 1. Map of study area. Red points are larger known sinkholes from Hubbard (1983).

number of only the largest depressions in the region from stereophotography and 20-foot contour 1:24,000 scale topographic maps.

The rocks of the region are composed of Paleozoic sedimentary carbonate and siliciclastic rocks that were faulted and folded during the Alleghanian orogeny, and erosion has left the core of the ancient Appalachian mountain range exposed at the present land surface. Karstification in the study area has resulted in a mature, dissected karst surface of moderate to low relief, with 90 m total elevation range and a mean elevation of 180 m above sea level. Sinkholes and karstic depressions generally occur as a result of cover-collapse or suffosion processes within the residuum overlying the carbonate bedrock; the thickness of residuum varies between 0 to upwards of 10 m. Bedrock structures (folds, faults, and fractures) exert strong control over the locations of karstic depressions in the region (Doctor et al., 2008; Doctor and Doctor, 2012).

Methods Manual delineation of depressions

Airborne LiDAR was acquired over the study area between March 01 and March 09, 2011. Flights took place during leaf-off vegetation conditions and within one week of complete melting of snow cover. Conditions were thus ideal for obtaining a representative bare-earth elevation surface. The vertical accuracy of the delivered LiDAR data was within 9.0 cm root mean square error (RMSE) and the LiDAR point cloud was acquired at a nominal point spacing of 1.0 m; hydro-flattening breaklines were manually collected based on the LiDAR surface model. Although hydro-flattening was performed on areas of known water surfaces, depressions or sinks in the bare-earth elevation model were not filled in the delivered LiDAR data.

The bare-earth LiDAR elevation model was used to derive 1) a hillshade raster, 2) a slopeshade raster, and 3) a TPI raster. The hillshade raster was illuminated from azimuth 300 and an inclination of 20 degrees above the horizon and represented using a grayscale color ramp. The slopeshade raster applied a grayscale color ramp to the surface according to the slope of each pixel. The TPI raster was calculated using a circular annular window with an inner radius of 2 m and outer radius of 10 m (see Jenness et al., 2011 for details), and a grayscale color ramp applied to the resulting raster.

These three rasters were overlain upon a 1 m resolution orthorectified aerial imagery of the study region obtained in the years 2002 and 2008in a GIS using ArcMap© v. 10.0 software. Identification of closed depressions was conducted by close visual inspection within gridded areas defined by the LiDAR tile index; each grid tile region was 1.5 km square.

Depressions in the elevation surface were manually outlined by a single worker (the first author) with a minimum of five vertices per polygon. Upon digitization, each polygon was attributed with the method of recognition (from the field, the LiDAR elevation model, aerial imagery, or some combination of these), and some basic descriptive notes. Description of an individual feature was aided by toggling between LiDAR-derived rasters and georeferenced aerial imagery, and some aspect of the hydrologic condition was normally noted (e.g., ponded, ephemerally ponded, located within an ephemeral channel, takes water, flows as spring, etc.). In general, it was found that the LiDAR rasters were more reliable in terms of an accurately georeferenced dataset than were the aerial images, thus digitization was done on top of the LiDAR-derived imagery. Nonetheless, the georeferenced aerial imagery was critical for identifying false depressions that arose out of processing of the LiDAR bare earth elevation model, as noted by others (e.g., Seale et al., 2008).

Digital outlining of polygons created to represent depressions was best facilitated with the TPI raster at 40% transparency draped over the slopeshade raster (Figure 2). This combination of LiDAR-derived images best illuminated the variations in surface elevation in a manner that could be most readily outlined, avoiding pitfalls of a traditional hillshade surface such as deep shadows, overly highlighted areas, or poor illumination angle and inclination. Although the slopeshade raster helps define edges of features by darkening pixels of high slope (e.g., the edges of a collapsed sinkhole), it does not distinguish between regions of higher or lower elevation; thus, a haystack may appear similar to a sinkhole. Fortunately, the TPI raster permitted distinguishing between areas of higher or lower local elevation (darker areas are local lows, lighter areas are local highs). Thus, the combined use of slopeshade and TPI rasters greatly enhanced the visualization of depressions for manual digitization.


Figure 2. Comparative views of an area with multiple closed depressions in the Boyce quadrangle. In the lower left of each image is a cluster of manmade percolation pits (1); in the upper center are two sinkholes, one deeper than the other (2); in the upper right is a bedrock ridge surrounded by trees along a fence line (3). (A) Aerial image. (B) Hillshade of LiDAR DEM. (C) Slopeshade of LiDAR DEM. (D) TPI raster of LiDAR DEM (note: dark areas are depressions and light areas are ridges). (E) TPI draped over the slopeshade. (F) TPI draped over slopeshade, with manually delineated closed depressions. A red X indicates a false depression where building edges caused errors in the LiDAR elevation model.

Once the polygon data digitization was complete, the vector data were further attributed with geometric characteristics including area, perimeter, major and minor axis length (of an idealized ellipse), circularity index (deviation from area/perimeter ratio of a circle), and elliptical eccentricity. These geometric characteristics were examined to identify threshold values that could be used to filter out spurious depressions identified through the automated techniques.

The eccentricity of an ellipse (commonly denoted as e) is calculated as:

$$e = \sqrt{1 - \frac{b^2}{a^2}} \tag{1}$$

where a and b are one-half of the ellipse's major and minor axes, respectively. The eccentricity of an ellipse will be greater than 0 (a perfect circle) and less than 1. Thus, the elliptical eccentricity can be a useful measure of the shape of a possible depression. Based on the manual dataset, we found that an eccentricity of less than or equal to 0.98 worked as a good threshold for identifying true depressions. This eliminated many elongated depressions that appear within stream channels, road ditches, and other features that are unlikely to be true natural depressions.

Similarly, the circularity index is a measure of the deviation of a polygon from a perfect circle based upon its perimeter and area. Since a circle has the smallest perimeter to area ratio, a relationship can be established between the expected circular perimeter of a feature (based on area) and its measured perimeter to create an index of circularity (Circ_i):

$$Pe = 2\pi \left(\frac{\sqrt{A}}{\pi}\right) \tag{2}$$

$$Circ_i = \left(\frac{P_o - P_e}{P_e}\right) + 1 \tag{3}$$

Where A is area, P_e is the expected perimeter if the feature were a perfect circle, and P_o is the observed perimeter. After some experimentation, we used a circularity threshold of less than 1.7 to capture closed depressions while eliminating linear features

The smallest area of any of the manually delineated depressions was 7.3 m^2 , and the smallest area of the

field-checked depressions was 9.0 m^2 . In the following automated analyses, we conservatively chose an area cutoff of a true depression to be greater than or equal to 9.0 m^2 .

Automated generation of depressions by difference raster

Several useful tools for processing elevation data exist in ArcGIS. For most raw elevation data it is necessary to preprocess or recondition the DEM in order to create a 'hydrologically correct' elevation model. A hydrologically correct elevation model is one in which every pixel in the surface slopes continually down gradient and out the edges of the elevation model boundaries. If a pixel (or region of pixels) is at a lower elevation than all of the surrounding pixels, the pixel acts as a 'sink', and surface flow will stop at that point unless the elevation is raised to a level at which flow would spill out of the sink. Therefore, reconditioning a DEM primarily involves three steps: 1) filling in sinks to their spill level (or 'pour point'), 2) determining the flow direction within each pixel once the sinks in the DEM are filled, and 3) determining the flow accumulation of each pixel in the elevation model. The flow accumulation raster can then be reclassified to define streams, or those pixels that accumulate the most flow.

The first step in the process uses the Fill tool (under the Spatial Analyst Toolsà Hydrology à Fill) in ArcMap v. 10.0. Reconditioning the bare-earth LiDAR DEM with this tool results in a new elevation surface with all sinks filled to their spill elevation. Since a filled pixel may still act as a sink if located within a larger depression, the process is iterative until all pixels within the depression are filled and the depression spills over. As a result of this process, stream channels in the DEM that pass under roads through culverts or beneath bridges may become dammed if the culvert or bridge has not been represented (i.e., cut into the elevation surface to stream level) in the DEM (Figure 3). For most larger streams and rivers, bridges and culverts are normally removed from the DEM during processing of the bare earth elevation model; however, in order to create a hydrologically correct DEM, all of the sinks within it need to be filled, thereby removing any evidence of natural depressions. As requested, the Shenandoah Valley LiDAR was not processed to have sinks filled by the vendor, thus necessitating the process by the end user. This presents an opportunity to partially automate



Figure 3. A) Artificial depressions created using the Fill tool in ArcGIS are shown with warm colors atop the LiDAR hillshade. Violet lines represent streams derived from the flow accumulation values applied to the Fill raster. Thick green outlines represent manually delineated depressions. Note that roads, railroads, driveways, and other features in the LiDAR elevation model act as 'dams' when streams pass beneath them through culverts. B) Culverts need to be manually digitized (short pink lines) and 'burned' into the DEM in order to allow streams to drain across the obstructions. Light green areas represent the resulting automated depressions from re-running the Fill routine on the reconditioned DEM. Some culverts were missed in the upper left, requiring further refinement through culvert addition.

the process of locating natural depressions. It also represents a challenge for determining true sinks.

Poppenga et al. (2011) suggested a workflow utilizing a least cost path analysis in GIS as an automated means of conditioning a DEM to remove these artificial dams; however, this process does not directly discriminate between true depressions and those that are artifacts of the Fill process, thus all depressions in a DEM will be drained unless selected otherwise according to some criteria. Poppenga et al. (2011) suggested using a threshold area of depressions targeted for drainage greater than or equal to 1,000 square meters, and depth greater than or equal to 1 meter and greater than 0.5 standard deviation of the difference grid. However, these thresholds may include true natural depressions in some karst areas, and exclude a number of depression artifacts. In order to preserve true depressions, the best means is to manually digitize polyline features corresponding to bridges and culverts at known locations, and 'burn' these lines into the DEM, or lower the elevation of the DEM along the linear feature to allow flow to pass through the obstructions. This was the approach taken in this study, and was accomplished using the DEM Reconditioning tool in ArcHydro Tools 2.0 (Maidment, 2002). Locating and digitizing actual culverts was facilitated using aerial imagery, and was assisted by the shape of the depression artifacts themselves such that any depression with a flat side parallel to a linear feature such as a road, railway, or driveway was immediately suspect, and targeted to be drained by addition of a culvert.

Once the reconditioned DEM was filled,

- 1. The original elevation DEM was then subtracted from the filled DEM to generate a 'fill-difference' raster that represented the depth of depressions in the original surface.
- 2. All values in the fill-difference raster that were greater than 0.18 m (18 cm) were extracted to a new raster. The minimum depth threshold of a pixel was conservatively chosen to be 18 cm, or twice the vertical accuracy of the LiDAR bare earth model which has a RMSE of 9 cm. This allowed for a great number of possible artificial depressions to be culled from the fill-difference data, and provides a 95% confidence level that a given pixel is a true depression in the elevation model.
- 3. The values in this threshold fill-difference raster were re-classified to an integer type raster such that pixels in the fill-difference raster with values of less than 0.1 m (10 cm) were classified as 'No Data'
- 4. The remaining pixels were converted into polygons, without simplifying, such that polygon boundaries exactly matched pixel edges.

The result is a polygon layer that is representative of the possible sinks from the reconditioned fill-difference raster based upon the accuracy of the LiDAR data alone. In order to refine these polygons down to those which may represent "true" depressions, we used a training polygon feature class of known depressions that had been identified in the field, and digitally outlined from the LIDAR data. Geometric properties of the true and candidate depression polygons were calculated, and the results were compared.

The geometric properties were calculated as follows:

- 1. The Zonal Statistics as Table tool was used to extract the MAXIMUM value (depth) from the fill-difference raster overlain by each polygon. The table also contains the area of the polygon, and a count of the number of pixels per polygon (which are both equal values for 1m square pixels).
- 2. The results of the zonal statistics table were joined to the attributes of the polygons.
- 3. The Zonal Geometry of each of the polygons was calculated and each polygon was attributed with its area, perimeter, and major and minor axis length of an idealized ellipse that would contain the polygon.
- 4. The eccentricity of an ellipse was calculated as a measure of elongation of a potential sink, with values between 0 and 1. A threshold value of 0.98 was chosen for the eccentricity based on visual examination of the manually delineated polygons, and any depressions above this threshold were removed.
- 5. The circularity index was calculated. A threshold value of less than 1.7 was used in order to compare to the elliptical eccentricity results.

Automated generation of depressions by Topographic Position Index (TPI)

While the TPI is useful for guiding visual interpretation, it is also useful for quantitative analysis and classification. We examined the potential for mapping closed depressions by thresholding, grouping, and selecting appropriate ranges of TPI values. We calculated TPI across the study area using the Topographic Position Index ArcGIS tool (Jenness et al., 2011) with an annular (i.e. doughnut-shaped) region. We used an inner radius of 2 meters and an outer radius of 10 meters to capture small closed depressions based on previous analysis in Jefferson County, West Virginia (Young, 2007).

Since the TPI calculates the local relative surface elevation of all pixels in the LiDAR DEM (above or below the local mean elevation), a threshold of the TPI values was used such that only depressional elevations are represented. TPI values were summarized within manually mapped, field-checked depression polygons (n=116) to determine appropriate thresholds that would separate significant depressions from shallow swales. TPI thresholds were assessed within sizebased classes of field mapped depressions (Table 1). Based on the overall mean of TPI, the TPI threshold was set to distinguish actual depressions as the overall mean TPI value minus one standard deviation, or -0.3 meters.

Additionally, the grouped TPI values characterize linear (e.g. gullies, road cuts) as well as circular depressional features, so we classified and selected features to eliminate non-circular depressions from further consideration. We did this by grouping together pixels from significant depressions into coherent features, and then assessing the shape of these features by computing an index of circularity using area and perimeter relationships in a manner similar to Seale et al. (2008).

By establishing a threshold on circularity of depressional features, elimination of linear or elongated depressions was possible. We also removed from consideration depressions that were located within a 2.0 m buffer zone of building footprints or within major stream channels as false depressions that were likely artifacts of the TPI analysis. Lastly, we set a size threshold of greater than or equal to 9 m² on features to eliminate small, spurious depressions that may have been the result of errors in the bare-earth LiDAR elevation model.

Table 1. Mean and standard deviation of topographic position index (TPI) values found at manually mapped, and field checked depressions.

Size Class	Mean TPI	SD TPI	Depressions (n)
$< 20 \ m^{2}$	-0.1702	0.1627	5
20-50	-0.1010	0.1385	11
50-100	-0.1592	0.1206	21
100-200	-0.1133	0.1698	18
200-500	-0.1706	0.2243	27
500-1000	-0.1232	0.1837	14
100-5000	-0.1034	0.1877	16
$> 5000 \ m^2$	-0.0194	0.1576	4
Overall	-0.1328	0.1740	116

Results

In order to evaluate the performance of the semiautomated fill-difference method, the dataset of manually delineated depressions was compared against the filldifference polygons. Each polygon in the manual dataset was assigned a confidence level as shown in Table 2.

Out of the 842 total manually delineated depressions, 594 were captured by the semi-automated fill-difference method thresholded to 18 cm maximum depth (70%). However, the manually delineated depressions that were greater than 18 cm maximum depth totaled 600. Thus, the semi-automated method captured 99.5% of the depressions it was capable of capturing in the manually created dataset given the 18 cm depth threshold set for removing probable artifacts. In other words, 242 of the manually delineated depressions were shallower than the 18 cm maximum depth threshold used to filter out the fill-difference results. These additional depressions were included in the manual dataset because all depressions that could be seen in aerial imagery were included, regardless of depth. Many of these shallow depressions were likely ponded with water, thus appearing to be shallower in the LiDAR than they truly are due to hydroflattening or loss of point return intensity.

Of the 6 other manually identified depressions, one (a manmade retention basin) was outside of the 0.98 eccentricity threshold, three were drained during creation of the fill grid, and two were below the 18cm depth threshold in the fill-difference grid. A very small number of depressions (3) were artificially drained during the reconditioning of the fill grid, resulting in false negatives.

Out of the 116 possible field-checked sinks of highest confidence, 80 were captured by the semi-automated

Table 2. Identification method and confidence of	
manually identified depressions.	

Confidence Level	Identification Method	Depressions (n)
1	air photo	27
2	LIDAR	453
3	air photo, LIDAR	229
4	LiDAR, air photo	17
5	in field	116
	Total Depressions:	842

field-checked sinks, all except one were below the 18 cm maximum depth threshold obtained from the fill-difference grid. The one remaining depression had been drained by the addition of a culvert in the reconditioned DEM, and thus ended up being a false negative. Of the other depressions that were too shallow to be captured by the 18cm threshold, 12 additional depressions would have been captured if the threshold were relaxed to within the RMSE of 9 cm, or one standard error.
dynamic depression that were full-difference method

fill-difference method (69%). Of the 36 uncaptured

performed very well in capturing the manually delineated depressions. Before applying area and shape threshold criteria, the total number of depressions identified by the fill-difference method was 3154, nearly four times greater in number than the manually identified depressions. Many of these depressions were unlikely to be true sinks since they were of a very small area. Using 9 m² as a conservative area cutoff below which a fill-difference depression would be thrown out, 706 of the fill-difference sinks were removed, and all were less than 60 cm maximum depth. Also, many artificial depressions occur at the edges of structures due to artifacts introduced in the LiDAR processing. Using a polygon layer of building outlines obtained from the Department of Information Technology and GIS for Clarke County, Virginia, the depressions that intersected the building polygons within a 2.0 m buffer distance were removed from the dataset (n=124).

Finally, a large number of depressions appear within stream channels, and although meeting the area, depth, and eccentricity criteria are still artificial depressions within the LiDAR-derived fill-difference dataset. Both the elliptical eccentricity and circularity thresholds are attempts tofilter out these artifacts since they account for all but the most linear depressions, which are likely to be spurious. Linear depressions often are observed in gullies, ravines, and stream channels and are not true closed depressions. Using the flow accumulation raster to define stream paths at a threshold flow accumulation of 410,000 (a threshold visually consistent with stream channels in the LiDAR imagery), depressions that directly intersected the stream paths (n=779) were also removed. Applying these threshold criteria of 1) more than 18 cm depth, 2) elliptical eccentricity less than 0.98, 3) area greater than or equal to 9 m^2 , 4) not intersecting building outlines, and 5) locations outside of known stream channels, the number of depressions resulting from the semi-automated fill-difference method was 1695, or roughly twice the number identified through the manual methods (n=842).

By contrast, the thresholding, grouping, and shape identification of the TPI raster resulted in identification of 3980 total depressions; however, only 257 of these coincided with the 842 manually mapped depressions (Table 3). Likewise, only 39 of 116 field mapped depressions were identified using the TPI threshold of -0.3 meters difference from average elevation in the 2-10 meter annular window, a shape threshold (circularity index) of less than 1.7, and a size greater than 9 m^2 . All but 32 of the 3980 TPI depressions thresholded to circularity of 1.7 met the eccentricity criteria of 0.98. In general, the TPI method resulted in more numerous and smaller depressions than either the manual or the fill difference method. We acknowledge that there is redundancy between the elliptical eccentricity and the circularity threshold measures. While the eccentricity measure combined with the fill-difference method appeared to map more "true" sinks than the TPI method and circularity threshold, a more detailed comparative analysis is needed to fully evaluate the strengths and weaknesses of these measures.

Conclusions

Overall, implementation of the TPI method is much more time efficient than the fill-difference methods, and does not require re-conditioning of the original LiDAR DEM with known culvert locations. However, the fill-difference method was much better at capturing depressions of larger area, and suffered less than the TPI method from identifying artifacts as real depressions

Table 3. Results from applying thresholds to the TPI raster for TPI value, shape, and size to identify depressions.

Manual mapping method	TSI mapped	Average Area (m ²)
TSI sink, no manual equivalent	3723	19.89
1 - air photo	12	22.92
2 - LiDAR	139	29.88
3 - air photo, LiDAR	57	34.42
4 - LiDAR, air photo	10	32.30
5 - in field	39	27.18
Total:	3980	

in the LiDAR DEM. More work is needed to assess mapping performance at multiple TPI window sizes as the single scale analysis presented here may not capture the variation in depression feature area and shape.

It was found that a number of fill-difference depressions were evident in the results that were likely artificial, but had not been drained due to the uncertainty of culvert locations. Thus, additional work is needed to cull out possible artificial fill-difference depressions 'dammed' against roads where culverts were not identified in aerial imagery. Fieldwork targeted at defining culvert locations would likely prove fruitful for mapping sinkholes from LiDAR, perhaps as much as the effort expended to map the locations of depressions themselves.

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DELINEATION AND CLASSIFICATION OF KARST DEPRESSIONS USING LIDAR: FORT HOOD MILITARY INSTALLATION, TEXAS

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Abstract

The Fort Hood Military Installation is a karst landscape characterized by Cretaceous-age limestone plateaus and canyons in Bell and Coryell Counties, Texas. The area is located in the Lampasas Cut Plain region of the Edwards Plateau and is stratigraphically defined by exposures of the Fredericksburg Group. Spatial interpolation of 105 km2 of the Fort Hood Military Installation provided depression data that were delineated and classified using geoanalytical methods. Most of the karst features within the study area are predominantly surficial expressions of collapse features, creating windows into karst conduits with surficial exposures of epikarst spatially limited.

The increasing capabilities of GIS (Geographic Information Systems) and accuracy of geographically referenced data has provided the basis for more detailed terrain analysis and modeling. Research on terrain-related surface features is highly dependent on terrain data collection and the generation of digital models. Traditional methods such as field surveying can yield accurate results; however, they are limited by time and physical constraints. Within the study area, dense vegetation and military land use preclude extensive traditional karst survey inventories. Airborne Light Detection and Ranging (LiDAR) provides an alternative for high-density and high-accuracy three-dimensional terrain point data collection. The availability of high density data makes it possible to represent terrain in great detail; however, high density data significantly increases data volume, which can impose challenges with respect to data storage, processing, and manipulation. Although LiDAR analysis can be a powerful tool, filter mechanisms must be employed to remove major natural and anthropogenic terrain modifications resulting from military use, road building and maintenance, and the natural influence of water bodies throughout the study area.

Introduction

The Fort Hood Military Installation is located within the Lampasas Cut Plain region of the Edwards Plateau in Bell and Coryell counties (Figure 1). The plateau topography is mostly flat over broad drainage divides and becomes rolling in areas proximal to streams, exposing Cretaceous carbonates from the Fredericksburg and Washita Groups (Figure 2). The climate of the Edwards Plateau is sub-humid and becomes increasingly arid to the west and cooler to the north. Courtesy of the Gulf Stream, prevailing winds are generally from the south and the general decrease in moisture content of Gulf air as it flows northwestward across the Plateau is the controlling factor responsible for this difference in moisture regime (Bradley and Malstaff 2004). Soil development is minimal on the upper plateau over the



Figure 1. Owl Mountain study area within the Fort Hood Military Installation.



Figure 2. Stratigraphic column of the Trinity, Fredericksburg, and Washita Groups of the Lower Cretaceous.

Edwards Group; thicker soils accumulate at the base over the Comanche Peak and Walnut Clay units that dominate the valleys.

The study area is the eastern portion of the Fort Hood Military Installation known as the Owl Mountain province. The area is approximately 105 km2 and is bounded by Owl Creek to the north, Lake Belton to the east, Cowhouse Creek to the south and the live fire impact zone to the west (Figure 1). The area has been modified for military training purposes and grazing, and the present vegetation and geomorphology are a reflection of the multi-purpose land use and water availability. This area is home to several endangered species such as the Setophaga chrysoparia, Vireo atricapilla, a nesting songbird; Acer grandidentatum, a rare maple relict from the Pleistocene ice age found in slot canyons within the study area; and Croton alabamensis var. texensis, a rare shrub that has been documented in only a few locations in the United States (Picinich 2011).

Geologic Setting

The Owl Mountain province is a karst landscape characterized by local Cretaceous-age limestone plateaus

and canyons with rock outcrops, cliffs, sinkholes, caves, springs, and rock shelters. Strata from the Trinity (Glen Rose), Fredericksburg (Edwards), and Washita (Georgetown) Groups with patches of limestone, dolomite, chert and marl alternately crop out at the surface and as scarps along incised stream valleys in the area. These exposures have been described as mounds or shoals that developed in shallow water, high energy environments; possibly as part of the restrictive structure that enabled the deposition of the evaporitic material in the Kirschberg lagoon to the southwest (Fisher and Rodda 1969). The trend of these formations, formed across the axis of the Belton High (Figure 3), follow the model presented for Moffatt Mound (Amsbury et al. 1984; Brown 1975) (Figure 4). The Moffatt Mound area consists of thicker, more well-defined outcrops of Edwards Group strata that are lithologically distinct from the main Edwards reef trend. The eastern section of the Fort Hood Military Installation, including the Owl Mountain province, is thought to be a remnant of one of these isolated structures (Amsbury et al. 1984).

Early geologic mapping by Barnes (1970) shows the undivided Edwards Group conformably overlying the Comanche Peak Limestone. Most of the units are relatively unaltered and generally flat-lying or slightly



Figure 3. Location map showing the regional features influencing the depositional environment for the Fredericksburg Group on the Comanche Shelf behind the Stuart City Reef Trend. The Belton High, a smaller, structural high similar to the San Marcos Arch, provided the depositional environment for the mounds and shoals behind the main reef structure.



Figure 4. Conceptual depositional model of the carbonate Moffat Mound structure. (Bryant 2012, adopted from Amsbury et al. 1984).

dipping to the east, although the top surface of the Edwards does show some undulation. Deposition of these units began approximately 110 mya on the Comanche Shelf, which was constructed on the tectonically positive Llano and Devils River uplifts in Texas behind the Stuart City Reef complex (Nelson 1973)(Figure 3). The Comanche Shelf was bounded on the east and south by a relatively deep-water oceanic basin, the ancestral Gulf of Mexico, and on the north and west by an extensive shallow-water open marine basin, the North Texas-Tyler basin (Fisher and Rodda 1969).

Within the study area, the Glen Rose and Paluxy Sand formations provide the substrate for the overlying strata (Figure 2). The upper section of the Glen Rose lies underneath the exposed units and is composed of limestone, dolostone and marl that were deposited in a variety of environments such as marine, tidal-flat, reef and hyper-saline settings (Barnes 1970). The Paluxy Sand is a friable, fine- to very fine-grained, quartz sandstone with partial calcite cement that overlies the Glen Rose Formation. Although it may be present in the subsurface, no outcrops have been documented by current studies in the study area.

The Walnut Clay overlies the Glen Rose and Paluxy deposits and forms the lowland floor of the study area. Walnut deposits represent transgressive facies and are subdivided into six members; in the study area the Keys Valley Marl is the prominent member. This unit lies in gradational contact with the overlying Comanche Peak Limestone in the subsurface and is exposed at lower elevations (Adkins & Arick 1930). Specific facies within the Walnut Formation include mudstones, wackestones and packstones, containing fossil assemblages of pelecypods, echinoderms and gastropods. In the study area, well-cemented fossil beds of Texigryphaea can be found near the current base level of stream channels and along the shores of Lake Belton. The Comanche Peak Formation is a nodular limestone and marl sequence with a maximum thickness in Bell and Coryell counties of approximately 21 m. The Comanche Peak has transitional contacts with the underlying Walnut Clay and the overlying Edwards Group (Senger et al. 1990). Most of the Comanche Peak is not distinctly bedded, and their transitional contact can be readily distinguished in outcrop from the overlying Edwards. Fossil content and permeabilities within this unit are considerably less than the overlying Edwards Group.

The Edwards Group is a series of massive to thin-bedded limestones, dolostones and marls containing mudstone, wackestone, packstone and grainstone facies with chert nodules and rudistid biostromes. These facies form the cap rock of the study area and varies from rudistid rich limestone to vuggy, porous outcrops of peloidal and oolitic wackestone to packstone. The Edwards Group can be informally divided into four members, and although these informal designations have been described and named, most mapping and descriptions of the northern outcrops of the Edwards Group are not differentiated. Epikarst development is spatially limited with some spongework epikarst developing in areas with a thin veneer of soil.

The Georgetown Formation, a unit within the Washita Group, consists of fossiliferous limestone, argillaceous limestone and minor marl that have wackestone, packstone and grainstone facies. Pelecypods are diagnostic features of the Georgetown Formation, as well as vuggy porosity present in some of the facies. Although these rocks are included as part of the Northern Edwards Aquifer, none are mapped separately in the study area.

In the Owl Mountain province, the Walnut Clay, Comanche Peak and Edwards formations crop out at the surface (Figure 5). The lower valleys along creeks and rivers are covered by thicker soil and vegetative cover developing over the Walnut and lower portion of the Comanche Peak. Comanche Peak outcrops are exposed along the base of the plateaus, interfingering with exposures of the Edwards Group. The recharge zone of the uplands stands alone as a positive topographic feature directly coupled to the atmosphere. Precipitation is either directed into short stream segments and drainage basins or directly into the subsurface through joints, fractures, vugs, sinkholes and smaller conduits. This water will



Figure 5. Geologic map of the study area with mapped karst features including caves, shelter caves, springs, sinks, and seeps identified. Karst features were mapped by Reddell et al. (2011) and are part of the ongoing research at Fort Hood.

travel vertically or sub-vertically until it reaches a lower permeability unit; where it will then travel laterally to discharge as one of the numerous springs and seeps on the outer edges of the uplands.

Karst Development

The level of karst development within the study area is controlled primarily by lithology; where the Edwards Group is exposed to meteoric influences, the more advanced dissolution and karst development (Figure 5). Many of the sub-surface karst features are fracture controlled, displaying both local and regional trends (McCann 2012), with karst feature development controlled by lithologic and permeability boundaries within and between the contacts of the Walnut Clay, Comanche Peak and Edwards units.

Regional uplift of the Edwards Group as a result of the Laramide orogeny resulted in the exposure and partial erosion of these units, increasing secondary porosity and tilting the strata to the southeast (Elliott and Veni 1994). During the Miocene, faulting and subsequent uplift along the Balcones initiated the development of drainage systems and as the stream segments incised exposed rock, the intersection of fracture conduits with stream base level helped widen cavities and develop spring discharge outlets. Some karst development is controlled by bedding planes with springs, seeps, and rock shelters developing along the interface of lithological contacts between the Walnut Clay, Comanche Peak and Edwards units. To date, surface mapping by Reddell et al. (2011) across the entire military installation have identified over 300 caves, 80 springs, 667 sinks and 491 shelter caves have been delineated (Figure 5).

Most of the karst features identified within Fort Hood are coupled to the surface and exhibit solutional widening and overprinting by meteoric waters. Sinkholes and cave entrances are often small and associated drainage basins are spatially limited, generally covering less than one hundred square meters in area. In the study area, many sinkholes and cave entrances appear to have formed as upward stoping collapse structures and/or features that have been breached by surficial denudation (Bryant 2012). Cave development is commonly associated with high-angle scarps truncated by abrupt eroded edges of the plateaus in the eastern portion.

GIS Analyses

The increasing capabilities of GIS (Geographic Information Systems) and accuracy of geographically referenced data has provided the basis for more detailed terrain analyses and modeling (Liu, 2008). Through spatial interpolation of available LiDAR data, depressions associated with karsting can be delineated and classified over terrains using geoanalytical methods. Research on terrain-related surface features is highly dependent on terrain data collection and the generation of digital models. Traditional methods such as field surveying and photogrammetry can vield accurate results; however, they are limited by time and physical constraints. Airborne Light Detection and Ranging (LiDAR) provides an alternative for high-density and high-accuracy three-dimensional terrain point data collection (Liu, 2008). The availability of high density data makes it possible to represent terrain in great detail; however, high-density data significantly increases data volume, which can impose challenges with respect to data storage, processing, and manipulation.

Lidar

The LiDAR data used for this study were captured in March of 2009 by Optimal Geomatics (Optimal Geomatics, 2009). The raw data collected from the LiDAR surveys were processed using the software package DASHMap produced by Optech, Inc. (Optimal Geomatics, 2009). DASHMap generated a set of data points for three laser returns, the tree canopy (first return), lower vegetation and brush (second return), and bare earth (third return) in an LAS file by using both the GPS and inertial navigation system (INS) roll, pitch, and heading information recorded by the planes POS (Position Orientation System). The LAS files were converted and divided into multipoint shapefiles and stored in a geodatabase for simplicity. The database containing the LiDAR survey data was acquired from the Fort Hood Natural Resources Division and the bare earth LAS files were used to build the initial Digital Terrain Model (DTM) and Digital Elevation Model (DEM) used in this study.

DTM and DEM

The high density and accuracy of collected elevation points through the airborne LiDAR survey provide the basis for creating a geostatistical model that can then be further analyzed. In order to work within system memory limitations, a Digital Terrain Model (DTM) was built to simplify the management and manipulation of this large dataset (Esri, 2012). In order to perform detailed spatial analyses and utilize the numerous tools available through ArcGIS's Spatial Analyst, the model was converted into a raster format so that cell-by-cell calculations could be made.

A 1 m resolution DEM was found to be the best model to adequately resolve karst features in the study area without introducing a significant amount of error; the accuracy of the DEM was derived in accordance with the ASPRS Guidelines for Vertical Accuracy Reporting for LiDAR Data (Flood, 2004). The expected horizontal accuracy is 1/2000th of the flight height, which in this LiDAR survey was 2200 m above ground level, resulting in a horizontal accuracy of less than 1.1 m. The vertical accuracy of the DEM was found by calculating the root mean square error (RMSE) between validation points of known elevation and the interpolated elevations from the 1m DEM. The RMSE of the 1m DEM for the study area is 14.04 cm; therefore, the vertical accuracy of interpolated points is less than 27.52 cm.

Depression Identification

The study area has known karst development and by performing spatial analyses on the high resolution 1m DEM, sinkholes or depression features could be identified. To identify closed depressions within the study area, the flow accumulation tool was used to create a raster of accumulated flow for each cell in the DEM. Once the depressions were identified, the fill tool was used to create a filled DEM raster without closed depressions. The original DEM was subtracted from the filled DEM to identify only the closed depression features (Stafford et al., 2002). Depression features were delineated so that their spatial attributes could be measured and classified for further analyses. The boundaries for the depression features were delineated in a five-step process: 1) Convert depression raster to polygons; 2) Buffer polygons to incorporate immediately surrounding area as a depression; 3) Dissolve any overlapping boundaries; 4) Smooth the polygons to remove hard cell boundaries; and 5) Simplify the polygons to remove any extraneous bends. A single polygon represents one depression object; the depression delineation process identified a total of 9,175 depression objects in the study area. Depressions were classified using properties that relate to whether the feature is a naturally occurring karst feature; depressions which intersected or overlapped with natural and anthropogenic terrain modifications were removed progressively from the total list of delineated depressions.

Depression Classification

The depression identification process identified all depression features in the DEM, which means that depressions associated with river channels, roadways, and other man-made features were also identified (Liu and Wang 2008). In order to identify the depressions associated with karsting, the delineated depressions were filtered and classified by their spatial attributes to remove depressions as a result of natural and anthropogenic activities, and to identify any inherent spatial relationships that may exist.

Depressions were removed or classified by determining their spatial relationship to known anthropogenic and natural influences. Lakes or large bodies of water, roads, and stream locations were first used as classification determinants. Lake Belton, Cowhouse Creek, and Owl Creek, as well as smaller lakes and ponds, were delineated from aerial imagery and any depressions that were within 20 m of these water bodies were classified as being influenced by those water features (Wang and Liu 2008). Stream segments were delineated for the study area through the creation and classification of a flow accumulation raster (Figure 6). The cells with the highest flow accumulation, greater than 100,000 m2, were isolated and delineated as being a stream feature. Any depressions that were within five meters of a stream segment were classified as being influenced by a stream or river.



Figure 6. Stream segments were delineated for the study area through the creation and classification of a flow accumulation raster. The cells with the highest flow accumulation, greater than 100,000 m2, were isolated and delineated as being a stream feature and all depressions within 5 m of the stream segments were removed from the depression database.

The study area contains roads of all types and sizes from the long history of military use, so the major roads were digitized in a dataset (Figure 7). Major roads include large paved roads, tank roads, and pipelines that transect the study area. Any depressions that lie within 20 m of a major road centerline were classified as being influenced by this feature. Depressions were also classified based on their underlying geology. The Edwards and Comanche Peak formations are the only geological units in the study area known to support karst development therefore depressions occurring outside of those formations are likely to be artificial. Depressions that were located within the Walnut or alluvial deposits were identified and removed from the dataset.

The depth or range of elevation values that exist within a depression were also used as a classification determinant. Because the vertical accuracy of the interpolated surface was found to be within 0.275 m, depressions that were less deep than the accuracy level were classified as potentially artificial because those features cannot accurately be resolved. The depression in Figure 8 is a typical karst feature within the study area; this depression would have been within the limits of the LiDAR resolution, however

depending upon where the points were taken, could have been missed by the survey.

Finally, depressions were classified based on vegetation cover type. Depressions that occurred within the bare earth and disturbed herbaceous cover types were removed from the database. These areas are heavily altered by training exercises and military maneuvers and the resulting depressions would be artificially derived (Table 1).



Figure 7. All major roads within the study area were digitized to facilitate classification of depressions that were influenced by roads and infrastructure. All depressions within 20 m of the major roads were removed from the depression database.



Figure 8. Typical small depression found within the study area, with major and minor axes measuring 1.56 m and 1.43 m respectively, and a depth of .67 m.

After all classifications had been made and the depression database had been filtered by potential interference with natural processes and artificial structures, a total of 1,538 depressions remained in the database. A significant number of features intersected or overlapped with more than one classification type, with the most common parameter associations found between streams and roads, and secondly, between streams or roads and geology (Table 2).

Depression Density

Depression density maps were created to show the spatial distribution of delineated depressions before and after filtering across the study area. Point maps were generated to show the centroid point of each depression identified, and density values were found by using the centroid point of each depression object which depicts the number of depressions found within

Table 1. The table below categorizes the number of depressions that were removed by the filtering mechanisms used in the study. Many of the depressions were filtered by more than one mechanism; therefore the total number of sinks delineated and removed is greater than the total number of sinks in the database.

Type of Classification Interference	Filtering Mechanism	Number of Sinks Removed
Water Bodies	20 m	31
Vegetation	cover type	692
Roads	20 m	905
Geology	lithology	1,628
Streams	5 m	4,028
Depth	<0.275 m	4,091

Table 2. The number of classification interferences and the percent of the total depressions that were removed as a result of these filtering processes.

Number of Classification Interferences	Number of Depressions	Percent of Total Depressions
0	1,538	16.763%
1	4,659	50.779%
2	2,301	25.079%
3	589	6.420%
4	87	0.948%
5	1	0.011%
6	0	0.000%
Total	9,175	100%

a one square kilometer search radius. The density map of all delineated depressions shows that high-density regions are concentrated near major roads, large stream segments, areas of lower elevation, and within training areas currently used by the military (Figure 9).

The density map of depressions that did not intersect or overlap with any of the classification determinants shows that the densest areas are limited to topographically high regions of the study area (Figure 10), particularly those associated with high plateaus and steeper scarps; however some appear to be associated with anthropogenic structures and modifications not previously filtered.

Slope Analysis

Slope analysis of the study area was performed through the creation and classification of a raster image representing the slope per cell (Figure 11). Shelter caves previously mapped by Reddell et al. (2011) were plotted on the slope analysis map. These shelter caves may represent discharge features with limited connectivity to depressions at the surface. The slopes that were determined to be related to areas of known shelter cave



Figure 9. After the initial analysis, 9,175 depressions were identified. A kernel density map was generated with the highest concentration of depressions associated with major roads, streams, and training areas.



Figure 10. After classification and removal of the identified depressions, 1,538 remained in the database. A kernel density map for these remaining depressions was generated, showing the greatest accumulation in the northern part of the study area and along the shores of Lake Belton.

development are greater than 25 degrees from horizontal. The slopes found to be greater than 25 degrees are mainly limited to areas of scarp development, with most occurring along the dissected edges of stream segments across the northern part of the study area and along the shores of Lake Belton.

Conclusions

This study utilized LiDAR data to resolve depression features in the Owl Mountain province on the Fort Hood Military Reservation with an elevation model at a resolution of 1 m. Due to the limitations of the data, any depression features smaller than 1 m2 could not be resolved. While the majority of natural depression features related to karsting in the study area do not have depths greater than 1 m, any depression features whose depth was less than the vertical accuracy of the LiDAR survey were omitted because they could not be accurately interpreted. In addition, the study area has been extensively modified by past and current military use, thus depressions and other surface scars related to military use cover most of the study area and must be taken into consideration when interpreting results. The combination of heavy military use and high resolution elevation data make it extremely difficult to discern between whether identified depressions are natural or artifacts; therefore, models developed from LiDAR analyses at Fort Hood are assumed to have errors, both



Figure 11. Left: Slope analysis of the Owl Mountain province with shelter caves identified in study area. Right: Scarp development is greatest along the shores of Lake Belton; the interfingering nature of the Comanche Peak and Edwards Formation provides horizontal flow paths for surface waters and enhances shelter cave development.

in the inclusion of anthropogenic depressions and the exclusion of natural depressions.

Although LiDAR analyses can be a powerful tool, filter mechanisms must be employed to remove major natural and anthropogenic terrain modifications resulting from military use, road building and maintenance, and the natural influence of water bodies throughout the study area. The results of LiDAR analyses are directly related to the quality and density of the initial LiDAR survey, with accuracy and quality limited by time and monetary constraints. Because the resolution of the LiDAR survey determines the scale of ground features that can be resolved, limitations will exist based on the accuracy of the collected data.

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LOCATING SINKHOLES IN LIDAR COVERAGE OF A GLACIO-FLUVIAL KARST, WINONA COUNTY, MN

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Abstract

Sinkholes in Winona County, MN have been mapped four times since 1985 using different techniques including field observations, topographic maps, air photos and Global Positioning System (GPS) measurements. As of early 2009, these efforts had identified and inventoried 672 sinkholes in Winona County that are recorded in the Minnesota Karst Feature Database (KFDB) (See the KFDB at: http://deli.dnr.state.mn.us/). The acquisition of one-meter resolution Light Detection and Ranging (LiDAR) images has significantly increased the speed and accuracy of sinkhole mapping. One meter shaded relief LiDAR Digital Elevation Models (DEMs) for Winona County were visually scanned to compare sinkhole locations in the KFDB with the LiDAR images and to find new sinkholes in the LiDAR DEMs. The results of this method indicate that the number of actual sinkholes in Winona County could be as many as four times more sinkholes than identified by the pre-LiDAR surveys.

To automate sinkhole detection from LiDAR data at a regional scale, an algorithm was developed in MATLAB® based on image processing techniques. The algorithm has three steps. The first part detects potential sinkhole locations as depressions in the DEM using a morphological operation (erosion). The second part of the algorithm delineates sinkhole boundaries by automatically fitting an active contour (snake) around the potential sinkhole locations. In the last step, a pruning process, based on the relationship between depth and area of depressions, was applied to discard shallow depressions. The proposed method was evaluated on selected parts of Winona County. Evaluations of precision and recall returned positive results at 82% and 91% levels, respectively, which are sufficiently accurate to permit regional-scale, reconnaissance sinkhole mapping in complex landscapes.

Introduction

Sinkholes as surficial karst features can affect the water quality and quantity in underlying carbonate aquifers, as part of the hydrological cycle. Sinkholes have become convenient (but inadequate) indicators of the presence of karst processes/aquifers and are routinely used in zoning and resource management decisions by regulators. Complete, accurate inventories of sinkholes are therefore needed, but are difficult to produce and require ongoing updating.

Various techniques and methods are used to map sinkholes including topographic maps, air photo interpretation, and GPS measurements, as well as field observation. It is difficult to map all sinkholes using the above methods at a regional scale. For example, depending on the contour interval (map scale) on topographic maps, small- or medium-sized sinkholes are not detected. Also, sinkholes under forest often cannot be seen on the aerial photos. However, the recent availability of one-meter (elevation) resolution of DEMs derived from LiDAR has significantly increased the speed, accuracy and completeness of sinkhole mapping at the regional scale.

A simple method to map sinkholes using one-meter resolution of LiDAR data is to create hillshade images in the ArcGIS (ESRI, 2012) environment and then visually scan the hillshade image at varying resolutions to identify sinkholes. They can also be compared to air photos, available on such websites as Google Earth and Bing Maps. Although visually scanning is simple and accurate, it is laborious and time-consuming, especially for large regions. Also, sinkhole characteristics like area, perimeter and depth can only be measured or determined manually using visual techniques, which is very tedious and can be prone to accuracy problems. An automated method to locate and measure sinkholes from LiDAR data would significantly improve the speed and efficiency of sinkhole mapping from LiDAR data sets. Filin and Baruch (2010) proposed a method to automatically detect sinkholes and associated characteristics on a large scale. They detected the inner part of sinkholes using second-order partial derivates by arranging the Hessian form, H.

$$H = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{xy} & Z_{yy} \end{bmatrix}$$

where Z is the elevation from LiDAR DEM data. Then, they applied the active contour method (Kass et al., 1988) to delineate sinkhole boundaries. They used several validity tests, i.e. a compactness test and fitting a local bi-quadratic surface to the points surrounding the sinkholes for comparing the relative depth of inner point to adjust surface, to distinguish the sinkholes from shallow depressions.

Study Area

Winona County in southeastern Minnesota is part of the Upper Mississippi Valley Karst (Hedges and Alexander, 1985). Karst lands in Minnesota are developed in Paleozoic carbonates and siliciclastics. As shown in Figure 1, the lower Ordovician Prairie du Chien Group, containing sandy dolomite and quartz sandstone, forms a karst plateau across much of Winona County. Most surficial karst features including sinkholes are only found in the areas where the sedimentary cover bedrock surface is less than 15 m (50 ft) thick (Figure 2).

The mapping of sinkholes in Winona County in southeastern Minnesota began in the early 1980s. Dalgleish (1985) conducted the first survey of sinkholes in Winona County as part of the Minnesota Geological Survey's development of the Geologic Atlas of Winona County (Balaban and Olsen, 1984). She identified 535 sinkholes in Winona County, many of which had been filled, using the traditional tools of field work, topographic maps and air photo interpretation. The sinkhole locations were compiled on paper 7.5' U.S.G.S. topographic quadrangles and, at a later date, digitized. Magdalene (1995) resurveyed sinkholes to update the sinkhole database in



Figure 1. Bedrock geology and distribution of sinkholes in Winona County.



Figure 2. Map of Minnesota karst lands.

Winona County and recorded 72 more sinkholes. Gao and Alexander (2002) mapped additional sinkholes in Winona County using GPS technology.

Gao and Alexander also developed the Karst Feature Data Base (KFDB) for Southeastern Minnesota in a Geographic Information System (GIS) environment that includes sinkholes, springs, seeps, sinking streams and outcrops. The advent of GPS technology improved the accuracy of the more-recently inventoried sinkholes, but significant uncertainties remained in many sinkhole locations. Site specific field work added a few additional sinkholes to the KFDB, and 672 sinkholes had been inventoried in Winona County by early 2009.

This paper presents and compares two different methods to map sinkholes: 1) to visually scan LiDAR DEM images and 2) to develop an algorithm to automatically detect, delineate, characterize and validate potential sinkholes. The purposes of the first method are: 1) to compare sinkhole distribution in Winona County that had been mapped during previous decades with the new LiDAR DEM images; and 2) to map new sinkholes using the LiDAR DEM images. The goals of the second method are: 1) to apply an algorithm to identify sinkholes automatically in some parts of Winona County; 2) to delineate sinkhole boundaries; 3) to determine sinkhole characteristics like depths, areas and perimeters; 4) to prune depressions which may not be true sinkholes from the list; and 5) to compare the results from processing the algorithm with the visually scanned datasets in the KFDB in order to evaluate the accuracy of the algorithm.

Methods Visual Scanning of LiDAR DEMs

Airborne LiDAR was flown over the study area between November 18 and November 28, 2008. The vertical accuracy is 0.161 m root mean square error (RMSE) at a 95% confidence level (Loesch 2009).

One-meter shaded reliefs DEMs of Winona County derived from LiDAR were visually scanned at varying resolutions to identify sinkholes. As many as possible of the sinkholes in the early 2009 KFDB dataset have been relocated on LiDAR DEMs in ArcGIS to verify the sinkholes locations. In this process, additional sinkholes that were previously missed and new sinkholes which have opened since the original survey, were identified and mapped.

Air photos including Google Earth and Bing Maps proved valuable sources to help map sinkholes. Google Earth's coverage includes images from several different dates for some locations. "Birds eye" view feature from Bing Maps show low-angle, low-altitude, highresolution, pictometric photos from several directions for particular locations. Both types of coverage can be used visually to inspect the locations of sinkholes.

Erosion and Active Contour Algorithm

To automatically detect sinkholes and their boundaries, an algorithm in MATLAB® was developed based on image processing techniques. This algorithm has several steps: 1) detect local minimum points (seed points); 2) delineate depression outlines around each seed point; 3) characterize the perimeter, area and depth of each potential sinkhole; and 4) prune the list of potential sinkholes to differentiate sinkholes from shallow depressions that may not be true sinkholes. Finally, the remaining potential sinkholes were tested for validity as compared to known sinkholes that had been fieldchecked and entered into the KFDB.

The first step in the algorithm is to find local minimum points or the lowest point of depressions in LiDAR DEMs. The lowest point of depressions is identified through their geometric characterization using a morphological tool in MATLAB® called erosion. This tool processes images based on their shape. It compares the value of each pixel in the input image with its neighbors and assigns the value on a corresponding cell in the output image. The morphological operation uses structural elements, called kernel windows, to define the neighbors. It can be a matrix with any size.

The erosion operation compares the cell value with its neighbors in the kernel window and returns the minimum value in it for that cell in the output image. Figure 3 explains an example of the erosion process. In Figure 3A a schematic small depression is defined as a 5 by 5 matrix. Figure 3B shows the position of a 3 by 3 kernel window as it moves across the input image. As seen in Figure 3B, the value of the first element in matrix is compared with the highlighted cells that are covered by the kernel window. After that, the minimum value of these cells is assigned for the first element in the output image (in Figure 3C). The kernel window shifts to the next cell and this procedure continues until it reaches the end of image. The final result of the eroded image is shown at Figure 3D. The lowest point of the depression can be identified by comparing each cell in the original image (Figure 3A) with the corresponding cell in the eroded image (Figure 3D). The cells with the same value are assigned 1 and those which have different values become 0. As shown in Figure 3E, the lowest part of the sinkhole has the value of 1 while its surroundings have 0. Thus, the minimum point of the depression is located.

In this approach, the size of the kernel window influences the number of seed points identified. If the kernel window is too small, only a few cells are contributed and many local minima are identified. With a larger kernel window the number of cells included, the local minimum calculation increases and fewer seed points are identified.

Sinkhole depressions have various sizes and shapes, and they can sometimes be compound sinkholes: smaller sinkholes within a larger closed depression. Thus, to locate all of these depressions different sizes of kernel windows are needed; small kernel windows are optimal for small depressions and larger windows are better for larger depressions. Figure 4 shows the impact of the kernel window size on the number of seed points detected in LiDAR DEMs. Comparing kernel windows of 25 with 55 pixels illustrates that small depressions are detected with kernel size 25 while they are missed by kernel size 55.



Figure 3. The procedure of erosion function to find local minimum points.



Figure 4. Effect of kernel window size on detecting seed points on LiDAR DEMs.

In the second step of the algorithm, an active contour, a method for delineating object boundary from an image, was used to identify the depression boundary of each of the seed points. The boundary is a closed curve that is determined based on changes in flow of the elevation gradient in the surrounding region around the seed point (Kass et al., 1988).

The gradient is directly derived from the elevation map shown in Figure 5 (top Figure). The magnitude of the gradient corresponds to the slope of the depression (i.e. white cells in the edge map, gradient map, shows the maximum slope of a depression). It is possible to fit a curve around the seed point passing through cells, each with a maximum gradient corresponding to maximum slope. This method, however, is known to be sensitive to initial conditions, such as initial radius, and the process may not converge to the actual boundary of the depression in many cases.

To address the convergence issues, Xu and Prince (1998) proposed a Gradient Vector Flow (GVF) that provides a more robust vector field based on the gradient. This vector flow function points toward the cells with



Initialization and iterative process results from active contour

Figure 5. In the EdgeMap, top figure, white cells correspond to the maximum slope of a sinkhole. In the bottom, the green vectors are determined by Gradient Vector Flow. These vectors point toward the edge of the sinkhole boundary where there is maximum slope. The red contours show initialization and iterative processing until the contours converge to the sinkhole boundary.

maximum slope, even in regions far from the depression's boundary. Figure 5 shows an example of an EdgeMap, and the output for GVF of a sinkhole. As evident in this figure, flow vectors point toward the edge of the depression boundary where the slope is maximized. Also, it is shown that in homogeneous regions where the gradient barely changes, the vector flow is nearly zero.

An active contour is a curve that fits pixels of an image where a provided energy function is minimized. In this application, the energy function is (partially) chosen to be the GVF, and therefore, once the active contour converges, it finds the locations around a seed point where the slope is at its maximum. As presented below, two parameters influence the curve movement in the active contour (Xu & Prince, 1998): a) internal forces coming from the curve itself and b) external forces extracted from the image data (i.e., GVF in this application)

$$\mathbf{E} = \int_0^1 \frac{1}{2} \Big[\alpha \big| \mathbf{X}'(\mathbf{s}) \big|^2 + \beta \big| \mathbf{X}''(\mathbf{s}) \big|^2 \Big] + \mathbf{E}_{ext} \big(\mathbf{X}(\mathbf{s}) \big) d\mathbf{s} \quad (Eq.1)$$

Where E is the total energy function, the external energy is determined from the GVF: = -f(x,y). The remainder, the interal energy function, controls the behavior of the curve. In particular, the selection of α and β (components of internal energy) determine the tension and rigidity of the curve. The tension parameters control how much force is exerted on the contour to make it smaller. The rigidity parameter controls the smoothness and bending of the contour. Finally, is a contour location defined as . The active contour is solved iteratively, and therefore it needs initialization. The bottom image in Figure 5 shows the iterative process to delineate a sinkhole boundary. Also note the better definition of the sinkhole boundary by the active contour function, compared with the EdgeMap.

Sinkhole Characterizations

Given the boundary of the depression, the depth, area and perimeter can be calculated for each individual depression automatically.

To calculate the perimeter, the distance formula is used:

$$\mathbf{P} = \sum_{i=1}^{n} \sqrt{(\mathbf{x}_{i+1} - \mathbf{x}_{i-1})^2 + (\mathbf{y}_{i+1} - \mathbf{y}_{i-1})^2} \quad (Eq. 2)$$

where P is perimeter for the individual depression, n is the number of boundary points, and and are the coordinates of the boundary points. As the LiDAR data has one-meter resolution, the area is simply computed by counting the number of pixels which are located inside the perimeter. Another parameter, depth, is determined by subtracting the median of all of the pixel values along the perimeter from the pixel value of the seed point. The formula is as follows:

depth = $z_{median perimeter} - z_{seed point}$ (Eq. 3)

where z is the elevation value derived from LiDAR data.

Pruning

The algorithm finds all local depressions in LiDAR DEMs. Filin and Baruch (2010) suggest different validity tests to separate local and shallow depressions from true sinkholes. One test is compactness. For example, as sinkholes often follow a circular shape, the only candidates accepted as sinkholes are those contour lines whose compactness is nearly 1 (i.e., close to a circle).

However, the compactness test could not apply in many Winona County sinkholes due to their irregular shapes. A significant number of true sinkholes will be eliminated if the compactness test is used in Winona County. So, another method is required to prune these shallow depressions.

To find a threshold for pruning, a typical area of Winona County which contains the most representative topography and sinkhole shapes was selected.

In the selected area, typical sinkholes were manually identified to determine the relationship between their area and depth. For each sinkhole, the perimeter was marked by drawing a polygon. Based on the polygon, the area of the sinkhole was calculated. Then, the depth of the sinkhole was obtained by subtracting the elevation of the deepest point within the polygon and the median elevation on the sinkhole's perimeter.

This "training" dataset was used to identify extreme sinkholes in terms of their size and depth. Two types of such sinkholes are defined: 1) The sinkholes with depths of at least 90%, compared to the depth of the shallowest field-mapped sinkhole, and 2) the sinkholes with depthto-area ratios of at least 90%, compared to the fieldidentified sinkhole with the smallest depth-to-area ratio. Using these two extreme types of sinkholes (see Figure 6), a minimum depth-to-area ratio test is established by passing a line through the two extremes. In the pruning step, those candidates whose depth vs. area falls below the depth-area extreme line are removed.

In order to increase the recall rate (Table 1), (possibly at the expense of decreasing the Precision rate), the y-intercept of the extreme line may be tuned such that all the extreme sinkholes (in the training dataset) are located above the test line. This is particularly important for sinkholes with small areas that are in the early stages of development, and thus their shallow depth may place them below the test line. To accommodate for these sinkholes, the y-intercept of the test was decreased by 0.1 meters for sinkholes whose areas were lower than 100 square-meters. For example, in the case of a sinkhole with an area of 100 square-meters and a depth of 0.36 meters, it will not be discarded, based on the test line. But, in the pruning, sinkholes with areas of less than 100 square-meters and depths of less than 0.26 meters will not be included in the inventory.

To evaluate this threshold, a smooth region with no sinkholes was selected and the algorithm was run (Figure 7). As expected, many depressions were detected. However, after pruning about 92% of them were eliminated. The three remaining depressions, False Positive (FP) points, are ponds behind artificial dams. This example clearly shows that the threshold works well.

Results and Discussion Visual Scanning of LiDAR DEMs

The previous mapping of Winona County sinkholes had recorded 672 in the KFDB through 2009. Table 2 compares the Winona County sinkhole data in the 2009 KFDB and the results of visual scanning of the Winona County LiDAR data set. The data produced four distinct groupings.

Group 1: 66 sinkholes had LiDAR locations the same as their KFDB locations. These sinkholes served as



Figure 6. Two extreme sinkholes in terms of depth and area are identified. The first extreme, in the lower left, are the sinkholes with depths of at least 90% of the shallowest sinkhole. The second extreme, in the lower right, are sinkholes with depth-to-area ratios of at least 90% of sinkholes with the smallest depth-to-area ratio.



Table 2. Comparison of the original KFDB with the

 LiDAR Sinkhole Data.

Sinkholes in 2009 KFDB			
Visible in the LiDAR DEMs		Sinkholes	Sinkholes visible in
Location not adjusted	Location adjusted	not visible in LiDAR DEMs	LiDAR but not in KDFB
Group 1	Group 2	Group 3	Group 4
66	168	439	
672			651

important learning tools. They helped to illustrate what Winona County sinkholes look like in LiDAR DEMs in terms of shape and size.

Group 2: 168 sinkholes are visible in the LiDAR DEMs, but at slightly different locations than were recorded in the KFDB. The difference in locations was attributed to location errors in the KFDB. The old data was explicitly known to have location errors up to hundreds of meters. LiDAR allowed determination of more accurate locations for those sinkholes and to quantify the location uncertainty in the earlier data. The range of relocation adjustments was between 1 to 180 meters. Most of the location corrections were in the 10- to 30- meter range (Figure 8). Sinkhole location errors in the pre-LiDAR data included field location errors, changes in projection from NAD27 to NAD83 and accumulated typographical and transfer errors in 30+ years of record keeping (through several generations of data storage media). Quantification of these location errors was important in the definition of Group 3.



Figure 7.

Yellow points are identified as shallow depressions by pruning so they are removed from inventory. These points are located below the test line in Figure 6. Points in blue are depressions near the road. They are removed by the buffer tool in ArcGIS. The red points are False Positive (FP) points. They are located above the test line but they are not sinkholes. They are ponds behind dams or in ditches.

Legend

Seed points

- False Positive (FP) points that will be remained after pruning
- Shallow depressions that will dicarded after pruning
- Points near road that will be removed using buffer



Figure 8. Histogram of the relocation distance.

Group 3: 439 (65%) of the sinkholes listed in the KFDB were not visible on the hillshade derived from LiDAR DEMs. Approximately two-thirds of the inventoried sinkholes have apparently been filled for agricultural use and other reasons. Some of the filled sinkholes, not visible on LiDAR, can be seen on aerial images. Because filled sinkholes have a thicker profile relative to the surrounding, visible soil moisture contrasts are detectable on aerial images under the right moisture stress conditions. As illustrated in Figure 9, sinkhole D0019 has been filled and is not visible on the LiDAR or the Bing Map, "bird's eye" view feature. However, D0018 and is seen on the Bing map but it is not visible on LiDAR.

Group 4: The high resolution of one-meter LiDAR DEMs facilitates the mapping of sinkholes with high accuracy and precision. The LiDAR covers the entire region, including many areas previously unsearched by field work, and thereby provides a synoptic view

of the entire county. In Winona County 651 potential new sinkholes, not listed in the KFBD, have now been mapped, as shown in Figure 1. Field checks are necessary to verify which LiDAR features are sinkholes and which are other features. If all of these features are sinkholes, they will nearly double the number of mapped sinkholes in Winona County. If the ratio of two filled sinkholes for each currently open sinkhole holds, then Winona County may have up to four times as many sinkholes as are listed in the KFDB, based on visual mapping.

Erosion and Active Contour Algorithm

A small region of southwestern of Winona County, Minnesota was selected to evaluate the best parameters for the active contour method including examining the initial radius. As mentioned in the method section, the active contour is solved iteratively and then it needs initialization. Therefore, an initial radius is defined around each seed point and an iterative process finds the boundary around the seed point.

As seen in Figure 10, the sizes and depths of depressions range from very small ones with depths of less than 0.21 meter to very large ones with depths of 1.5 meter and greater. With this variety of sizes and shapes, it is impossible to identify all of the depressions with only one parameter. Therefore, different sets of parameters were examined and three of them were selected. The first parameter set uses a large kernel window size and the largest initial radius (15 m) for the active contour. This parameter set detects large and deep depressions. The second set, with the same kernel window size but different initial radius (10 m), identifies medium and shallower depressions. The third set with the smallest kernel window size and initial radius (5 m) is able



Figure 9. Comparison of sinkholes that is visible on Bing map and on LiDAR.



Figure 10. Sinkholes in Winona County have various size and shape range from very shallow and small to very large and deep.

to identify very small and shallow depressions. To validate the latter, the DEM in ArcGIS was resampled from 1-meter resolution to the finer resolution of 0.5-meter to detect very small and shallow depressions.

The problem of small depressions is that gradient changes are very smooth so that they cannot be easily identified with the 1-meter DEM resolution. In other words, there is no sharp transition from the minimum point of depressions toward their surroundings. However, with finer resolution, the gradient changes are more distinct, so the active contour method can identify the boundary for more shallow and small depressions. Figure 11 illustrates an example of three parameter sets for the active contour function. As Figure 11 shows, the parameter set 3 converges to depression boundaries better than parameter sets 1 and 2. This example clearly shows how the larger initial radius produces a better match with the depression boundary where the depression is large.

Validity test

To assess the precision of these methods, including erosion, the active contour, and this threshold procedure, 11 different parts of south-western Winona County with sinkholes of various sizes and shapes were selected and the procedures were run. Results show pruning removed significant number of shallow depressions; however, some of them have remained. The remaining points after pruning are not true sinkholes; they are ponds behind dams, depressions in ditches, local depressions in quarries and points near stream beds or roads (Figure 12). Note that points near roads are removed using a buffer tool in ArcGIS, so they are not counted in calculating precision and recall.

As seen in Figure 7, most of the depressions are shallow local depressions (less than 0.15 meter depth). Such shallow depressions are farmed across and are typically not considered sinkholes by the landowners. However, they



Figure 11. Three different parameter sets for active contour. The red has the initial radius (5 m), the blue has the initial radius (10 m) and the yellow has the initial radius (15 m).



Figure 12. Local depressions have remained after pruning that called False Positive (FP). They are located in ditches and quarries.

may be filled paleo-sinkholes or new subsidence sinkholes, or maybe the result of non-karst processes. Thus, a method to isolate these subtle local depressions was needed.

Although pruning discards most of shallow depressions, true sinkhole may also be removed. Based on the threshold,

sinkholes with area larger than 600 square-meters and depths of less than 0.6 meter are removed. In Figure 13, a sinkhole with an area of 1800 square-meters has a depth of 0.46 meter: so it plots below the test line in Figure 6 and is eliminated. However, the number of true sinkholes which are discarded by this pruning is very low compare to the number of shallow depressions defined.

After pruning, the results show out of 127 initial sinkholes identified, 97 of them were detected correctly, based on field-verified data in the KFDB. These are called true positives (TP). Of that sample, 21 of them are false positives (FP), which mean they are not sinkholes but have remained after pruning. The majority of these points are located in ditches and quarries. The remaining 9 sinkholes were not detected by these methods or were discarded by pruning. These are called false negatives (FN). Consequently, the precision and recall results were calculated for the algorithm.

The precision for the selected region in southwestern Winona County is 82%. This means that 82% of the detected sinkholes are true sinkholes, and the remainders are false positives. The recall is 91%, which indicates this method only misses 9% of sinkholes.

Considering the heterogeneity of Winona County (complex topography, woods, quarries, natural watercourses, man-made features, etc.) the algorithm method works wells to detect sinkholes. This automatic method can be refined using human supervision to increase the precision and recall.



Figure 13. Sinkhole with an area of 1800 square meters and a depth of 0.46 meters is eliminated through pruning.

Conclusions

The advent of high resolution LiDAR DEMs facilitates accurate and thorough sinkhole mapping. In the visual scanning process, comparing LiDAR data with KFDB classifies sinkholes into four groups: KFDB sinkhole locations which are the same as LiDAR locations; KFDB sinkhole locations slightly different from LiDAR data; KFDB sinkhole locations that are not visible on LiDAR; and additional sinkholes which are not listed in the KFDB. Comparison of these two data sets indicates that Winona County probably contains up to four times as many additional sinkholes as are indicated in the KFDB.

To improve the speed and efficiency of sinkhole mapping, an algorithm was developed to detect sinkholes automatically. To assess this method, selected regions in southwestern Winona County were analyzed. First, the erosion function in MATLAB® was used to find seed points on LiDAR DEMs. Then, the active contour method was applied to identify depression boundaries based on seed points. Next, the list of potential sinkholes was characterized. Finally, a threshold was set, using the relationship between area and depth, to distinguish true sinkholes from other local depressions. After this pruning, the precision shows that 82% of detected sinkholes are true sinkholes and the remainders are false positives, compared to sinkholes that were field-located and in the KFDB. The majority of the false positives appear to be located along natural watercourses, ditches or roads or in quarries. Additionally, this automatic method finds 91% of sinkholes correctly, and misses only 9% of sinkholes detected in the field.

Considering the region to which the method was applied, with a variety of features (such as wetlands, woods, natural watercourses, ditches, quarries and manmade features), the precision and recall is sufficiently reasonable to map sinkholes.

In future work, this method will be applied for other areas of Winona County, the results will be compared with the KFDB, the LiDAR DEMs will be visually scanned and then all features identified will be field checked.

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