KARST TOPOGRAPHY: NONINVASIVE GEOPHYSICAL DECTECTION METHODS AND CONSTRUCTION TECHNIQUES

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ABSTRACT

The objective of this project was to investigate the current state of the practice with regards to karst detection methods and current karst construction practices and to recommend the best practices for use by the Virginia Department of Transportation (VDOT). A comprehensive review of literature available on the subject was conducted. Various karst detection technologies were summarized with respect to conditions for usage and relevant specifications. In addition, common karst mitigation / construction techniques were also summarized. Recommendations for the management karst by VDOT were drafted.

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FINAL REPORT

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INTRODUCTION

Karst terrain is the geological phenomenon occurring when an area of sedimentary rock is dissolved by the action of groundwater (usually on limestone, dolomite, or marble), forming an area characterized by underground caves, fissures, and sinkholes, of which, cover-collapse sinkholes are the most prevalent (Fig. 1).

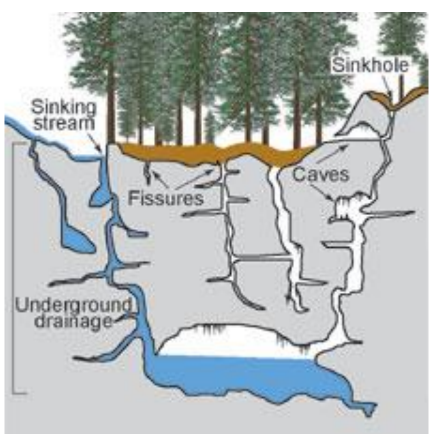

Figure 1. Karst Terrain Diagram (Environmental Science Institute, 2012).

Sinkholes are developed by two main mechanisms. The most common involves the upward raveling of soil over a cavity in the bedrock and the development of a soil arch (Sowers, 1978). Sinkholes at the surface develop as a result of the chemical dissolution of the bedrock in conjunction with the mechanical weathering of the overlying soils. Water table variability is the second method of sinkhole development. The strength of soil is largely dependent on the water content. Sudden changes in water content result in changes in effective stress and failures. The phenomenon of karst extends across about 25% of the globe (Veni, 2001), and across a large proportion of the United States (Fig. 2), and was known of long before geologists coined the word “karst” in the late 19th century (Harper, 2012).

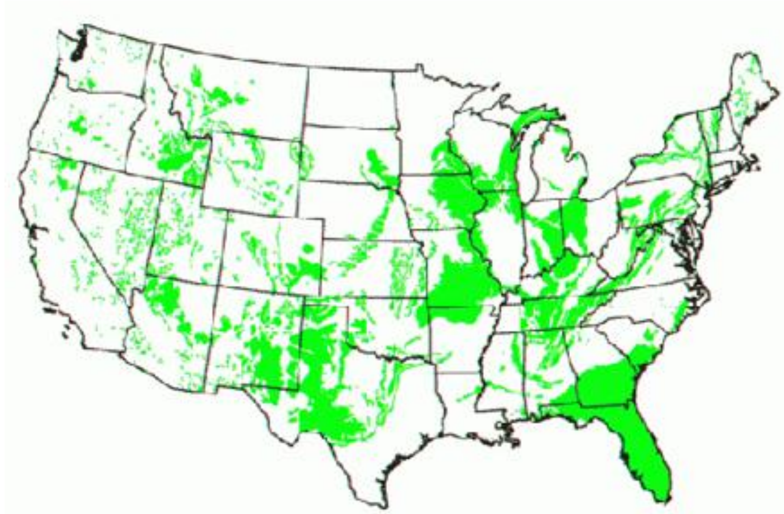

Figure 2. National Karst Map (Epstein et al., 2002).

Since then, the sinkholes formed by karst have been cited for the cause of hundreds of surface depressions, construction issues, building misalignments, foundations shifts, contamination of water supplies, and in many cases, local site collapses. Despite the potential geological hazards, these areas continue to be developed, further perturbing the subsurface topography. In order to maximize understanding of subsurface features, and minimize risk of adverse failure events, engineers have developed various noninvasive geophysical technologies to detect karst features, and numerous construction methods for building on, or near, these sites.

This project will outline a protocol for developers to follow when first evaluating a construction site, in the form of a literature review. While karst issues are global, this protocol focuses on cases within the United States. Specific focus will be on Virginia soil types whenever possible, due to work with the Virginia Center for Transportation Innovation and Research (VCTIR), and similar protocols from other states will be taken into consideration as this one is developed. The review will highlight the most common and effective techniques used to detect karst topography, the typical methods for construction over the topography, and the consequences of improper construction practices over karst terrain. This information will be used to create a set of recommendations for VDOT on selecting and implementing techniques in order to mitigate risk when developing in karsitic regions.

PURPOSE AND SCOPE

The geologic formations native to Virginia include several areas with karst topography, which is characterized the small and large-scale voids within the soil structure formed by the dissolution of soluble bedrock. It is estimated that three to five of VDOTs districts encounter karst during construction. Karst terrain is a difficult soil to work with since drainage within a karst soil can continually change the shape and size of karst voids and therefore significantly affect the strength of the soil itself. The possible variation of strength within karst soils causes additional challenges and concerns in the construction and maintenance of various transportation infrastructure components. From VDOT's perspective, the paramount issue associated with karst topography is the uncertainty and risk associated with karst terrain during construction projects. Since underground voids cannot be seen during construction, karst features can create difficulties during construction through changes in design and cost overages. VDOT does not currently have a set of guidelines addressing the appropriate construction practices to use within karst soils.

The major goals for this project were expected to be:

1. Critical Review of Issues Concerning Karst Topography – Using information in the literature, as well as consulting with the DOTs of other states with karst topography, the researchers will identify the major factors in the formation and subsidence of voids within karst topography, current methods used for void detection and the current construction practices within other states when dealing with karst topography.

2. Catalog VDOT Construction Projects in Karst Topography – The research team will catalog VDOT projects built specifically on karst topography and document the construction practices used and any occurring failures (sinkholes, etc…). The possible cause of any failures will also be investigated and documented.

3. Identify Commonalities within the Catalog - Using the catalog from Task 2, similar construction projects or results will be grouped into generic karst "situations". Possible groupings of construction projects might be classified by the physical characteristics of karst, depth from construction to weakened area, or perhaps some other variable seen after Task 2 is completed.

4. Recommendations for Future Construction Projects in Karst topography - The data from Task 3 will be compiled and recommendations will be made on how to proceed with future construction projects according to the situations identified in Task 3.

METHODS

Literature was reviewed on the current state of the practice with respect to the investigation of and construction practices for karst terrain in other states. The search focused on peer-reviewed research and literature sources. Search tools included Engineering Index, TRISWorld, Mechanical and Transportation Engineering Abstracts, and VDOT OneSearch databases. Specifications produced by various agencies were analyzed and examined for potential applicability to karst terrain construction activities overseen by VDOT.

Cataloging of current and past VDOT projects involving karst was not completed as per the project goals due to unavailability of data within VDOT project records that tracks karst occurrences within projects. This failure is considered to a greater degree in the Discussion section of this report.

RESULTS

Karst varies across the country depending on geology. While Florida exhibits the potential to develop large sinkholes, the method in which these sinkholes develop is quite different from the development of sinkholes in Virginia. In light of this, this research attempted to match the cited literature to areas of the country with similar soils / topographical features as those found in Virginia. Additionally, while the literature search included various types of karst voids (caves, fissures, etc.) more focus was applied to literature involving sinkholes, since they are the most common karst feature that develops along Virginia's roadways. Within the literature review of karst's current state of practice, two topics were researched: technologies that could detect voids in regions with known karst, and construction methods that could be used to mitigate / stabilize known voids.

The following noninvasive geophysical detection technologies were examined:

- Electrical Resistivity Imaging
- Ground Penetrating Radar
- Seismic Surveys
- Microgravity Surveying

Noninvasive Geophysical Detection Methods

There are various methods available to detect karst features. Traditional methods utilize soil/rock borings and percussion probes, however, these methods both require ground penetration and provide insufficient information about the subsurface (Roth and Nyquist, 2003). Non-intrusive methods have been developed in attempt to remedy some the shortcomings of standard penetration technologies. Some of the more effective noninvasive geophysical detection methods include: two dimensional resistivity imaging, ground penetrating radar, seismic surveying, microgravity surveying, and geophysical methods in conjunction with analytical and numerical modeling. Each method above can be used independently, however, in order to construct the most accurate subsurface models, using at least two (or more) of these methods is advised.

Electrical Resistivity Imaging

Two dimensional electrical resistivity imaging is one of the more common site investigation methods used for detecting karst features. This method is best used when soil layers consist of highly conductive clays, where ground-penetrating radar is ineffective (Roth and Nyquist, 2003). As well as for detecting air voids before a sinkhole has formed, due to the high contrast of conductivities between air and soil (Roth et al., 2002). The technology uses electrodes to measure the electrical conductivity of the soil at different depths. Once an initial site survey reveals potential for karst features, engineers place electrodes in the ground at known spaced intervals. Figure 3 shows a typical layout for a dipole-dipole resistivity survey.

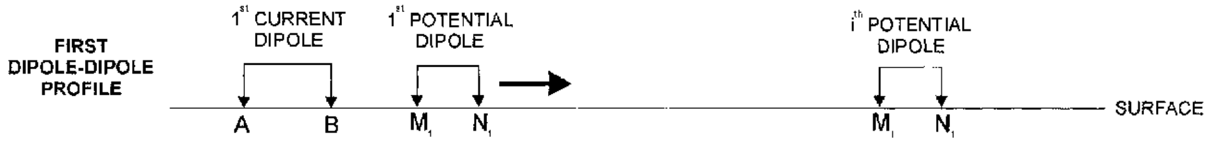

Figure 3. Dipole-Dipole Resistivity Survey (Van Schoor, 2002).

As seen in the figure, probes are placed at known intervals along the survey line, and measurements of the electrical potential between the probes are taken. Using two probes, they then induce an electric current to the soil and measure the electric potential between the buried electrodes. From this data, the conductivity of the soil can be calculated (Van Schoor, 2002). Since different types of soils have different conductivities, engineers can analyze this data and create a profile of soil types as a function of depth, giving them a good understanding of what soil layers lie beneath the surface layer (Anderson, 2008). Clays typically have low resistivities usually less than 100 ohm-m, intact rock around 400 ohm-m, and air filled voids have high resistivities around 2000 ohm-m (Missouri Transportation Institute, 2006). The large difference in resistivity between air and clays/rock is what makes electrode resistivity imaging a good method for sinkhole detection. In order to gain a thorough understanding of the subsurface site, many measurements are taken. Instead of using a single row of electrodes, engineers will often lay the electrodes out in a grid pattern to collect much more data. This type of layout will result in data that can be modeled in a two dimensional image. Oftentimes engineers will use an array to analyze the data to form an image of the subsurface soil layers, allowing them to better visualize the soil types, and detect any potential air voids. While three array methods exist the Wenner, Schlumberger, and dipole-dipole, a combination of these three arrays provides the best image of subsurface features; however, this method requires far more data collection, making it more expensive. Figure 5 shows the different images that could be obtained when using the different types of arrays.

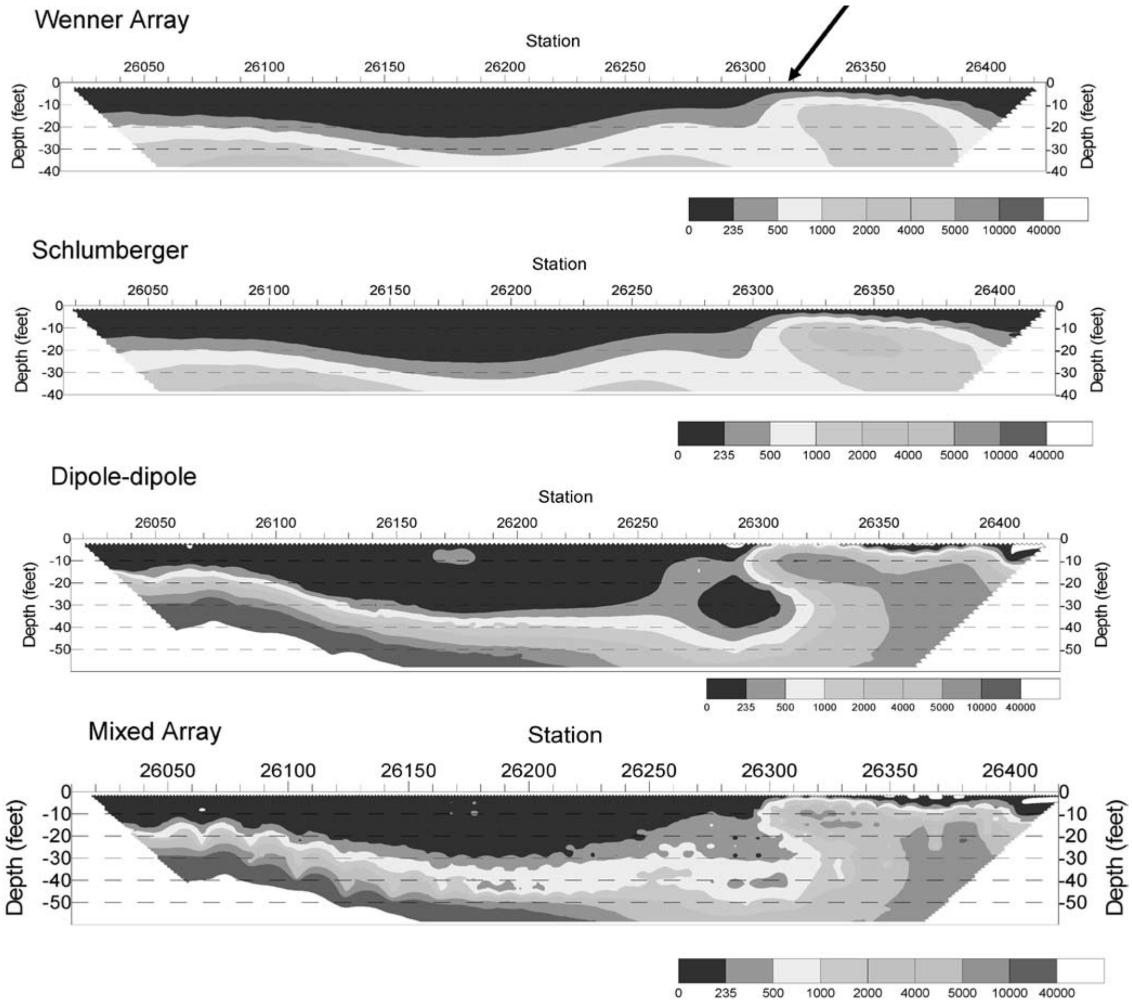

Figure 4. Arrays used in Data Reduction of Electrical Resistivity Imaging (Zhou et al., 2002).

As seen in the resistivity tomographs in Figure 4, the Wenner array is the least sensitive model, while the dipole-dipole seems to be the most sensitive. The arrow in the figure denotes the location of the sinkhole in this specific case study. When simply looking at the Wenner and Schlumberger array models, it is difficult to determine the existence of a sinkhole. These array types are good for determining the shape and depth of each soil layer, as well as what type of soil makes up each layer. Upon further investigation with the more sensitive dipole-dipole analysis, the location, depth, and size of the sinkhole can be determined much more easily. This is due to the higher sensitivity of the dipole-dipole array. The mixed array also offers a more detailed image of the subsurface soil layers. Unlike the Wenner, and Schlumberger models, the mixed arrays shows the soil layers in more detail, not only showing the main soil layers, but also the minor changes in each soil layer, which can be attributed to pockets of different soil types embedded in each layer. Usually most projects cannot afford, or simply do not require such a detailed image, in this case the dipole-dipole method is most efficient for sinkhole location (Zhou et al., 2002). However, it is recommended that any interpretation of a resistivity tomograph should not be used to pin point localized features in the field unless the data is confirmed by several intersecting transects with different orientations (Zhou et al., 2000).

Ground Penetrating Radar

Ground Penetrating Radar (GPR) is the most commonly used geophysical method for detecting karst, due to its simplicity and wide uses. GPR is best used to give engineers a basic understanding of what lies at shallow depths beneath soil surfaces. It is best used on flat surfaces, with fine grained soils. Figure 6 shows the typical GPR system setup. GPR units can vary in size, ranging from a push cart, to a system mounted on a truck.

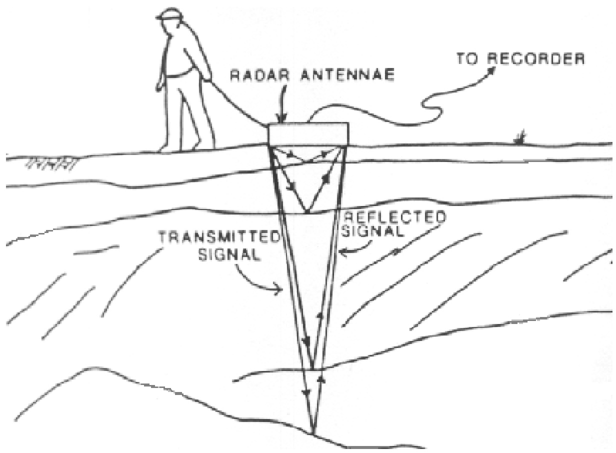

Figure 5. Ground Penetrating Radar (NJGWS, 2012).

Engineers drag a radio wave transmitter over the project site, as it slowly emits high frequency waves into the soil. These waves are reflected back to an antenna that records variations in the signal, producing a chart that can tell engineers what lies beneath the project site (Batayneh et al., 2002). The data collected can typically give a detailed image of the soil layers below the soil, and any existing anomalies such as pipe systems or sinkholes. The quality of the image is a function of signal strength and frequency. Higher strength signals allow for deeper penetration, but often times it is necessary to adjust the signal frequency to reduce interference (Tallini et al., 2006). Typically higher frequency waves have much less interference, but these waves cannot penetrate deep into the ground. Figure 7 shows a typical image obtained using GPR.

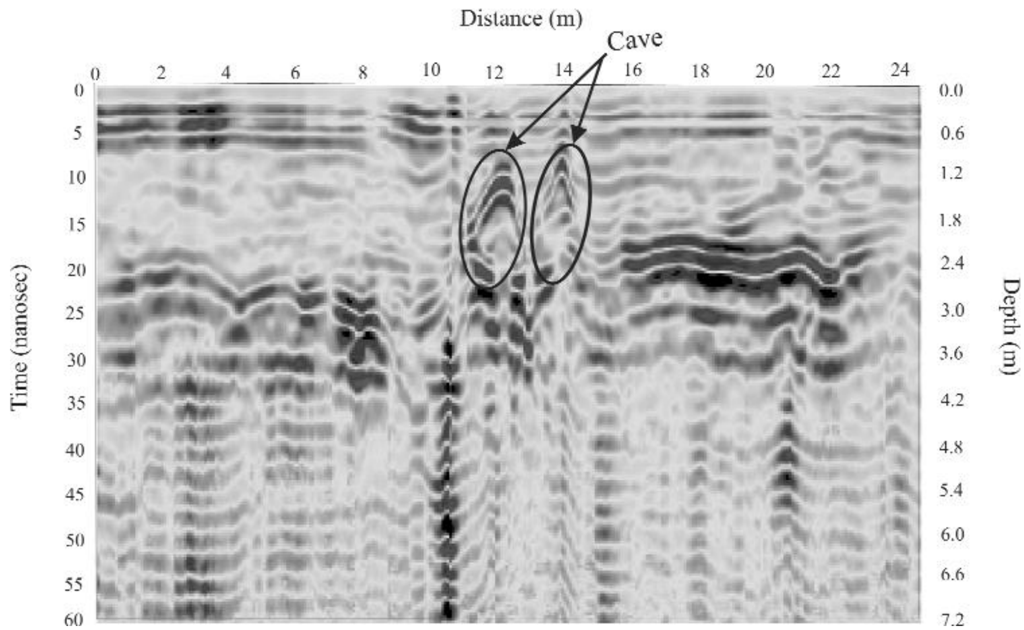

Figure 6. Typical GPR Image (El-Qady et al., 2005).

As shown in the figure, wave diffractions over a sinkhole can be clearly seen due to the difference in the materials of the filled sinkhole and the existing soils. The figure also shows some minor diffraction near the sinkhole. This can be attributed to different soil types than the bedrock lying below it. While GPR is a useful tool it often times requires additional data collection methods when cavities are detected. If such a void is detected, engineers cannot simply rely on GPR data acquisitions methods, instead a more in depth analysis of the soil is necessary to determine the nature and size of the karst feature.

Seismic Surveys

Seismic surveying has many uses, primarily when designing structures with deep foundation requirements, like bridges. These types of surveys often work best where there is a drastic difference between the rigidity of the medium and the karst feature, such as a sinkhole. Seismic surveying is based off of the travel times or spectral analysis of elastic waves. The Spectral Analysis of Surface Waves (SASW) method is used to determine the elastic modulus and layer thicknesses of soil layers. Continuous Wavelet Transform (CWT) is used more for void detection and characterization (Shokouhi et al., 2003). The refraction method shown in Figure 8 determines wave velocities through the different soil layers from field measurements.

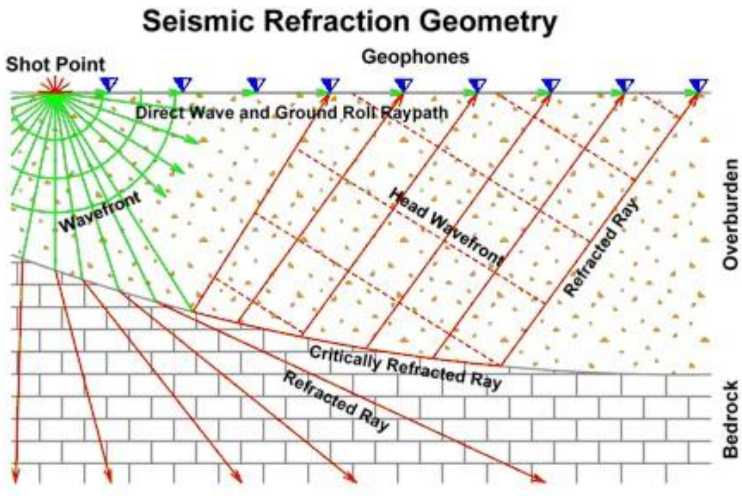

Figure 7. Seismic Refraction (Enviroscan, 2003).

As a wave is induced into the ground and reaches the interface between two different soil types, it will either travel along the interface or penetrate through to the next soil layer until the critical angle is reached. Once the critical angle is obtained the wave will then refract back to the surface (Hiltunen and Cramer, 2008). This data is then manipulated to understand the soil layers based off of the ways the waves either traveled through the soil media or refracted off of it. Seismic surveying incorporates the use of small explosives or weighted sledge hammers to induce a seismic wave into the ground where the speed of the wave is measured by geophones placed along a survey line. A geophone is placed at the location where the seismic wave is induced to serve as a control point from which all other geophones base their measurements. The buried geophones measure the time for the wave to reach them, and since the distance from the induction point is known, engineers can derive the wave velocities through each soil layer (Hiltunen and Cramer, 2008). These layer velocities tell engineers what types of soil lie beneath the surface, as well as the depth to bedrock, an important feature for bridge foundation construction (Harrison and Hiltunen, 2004). Once wave velocity measurements are taken the data is manipulated into an image to help engineers better analyze the data. Figure 9 represents a seismic tomogram with a potential pile location for a bridge foundation.

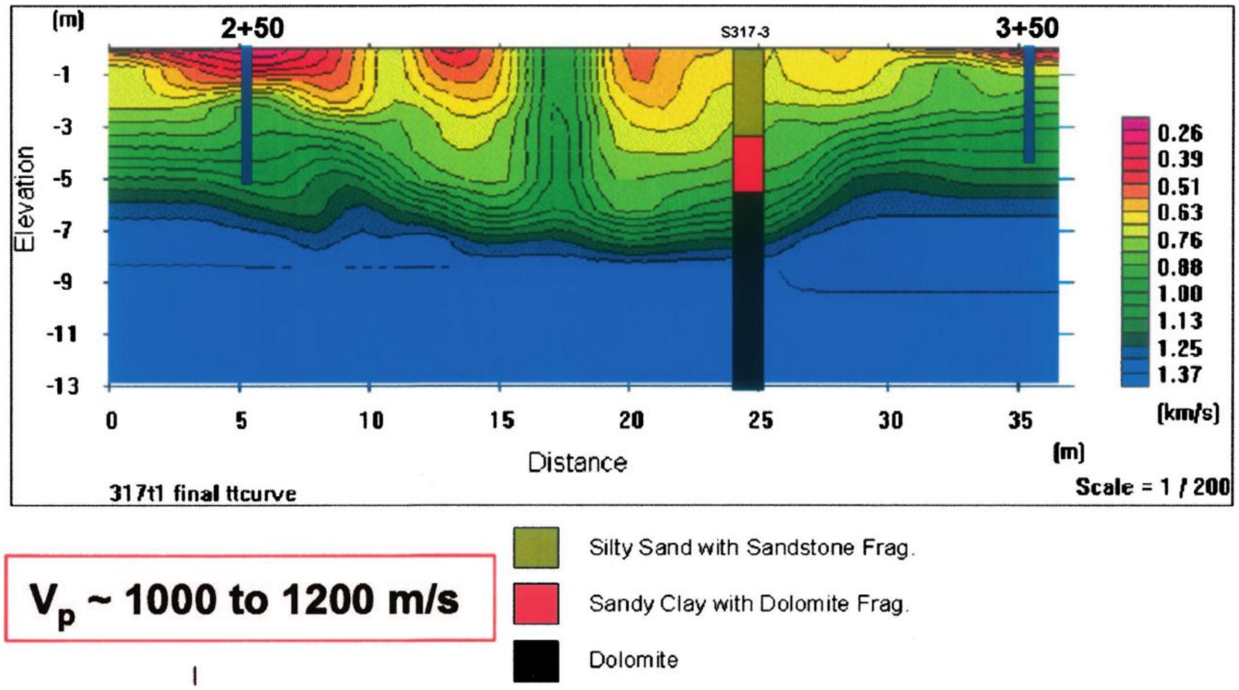

Figure 8. Seismic Refraction Data (Hiltunen and Cramer, 2008).

The different colors within the figure represent different soil layers derived from the wave velocities of the induced seismic waves. The vertical line at station three hundred seventeen represents a pile that will be used in the bridge foundation. These types of tomograms are very useful in determining the design lengths for each pile in a bridge foundation. While these methods are useful, they should not be used without additional borehole data collection methods. Seismic surveying should be used in the design stages for foundations, and the determination of borehole data collection points.

Microgravity Surveying

Microgravity surveying is a method used for determining karst features in urban areas where noise limitations or existing infrastructure would not allow for resistivity imaging or seismic surveying methods to be employed. Because voids in the soils have much lower densities than surrounding strata, microgravity devices are able to detect the minute changes in the gravitational pull of the earth in these areas. Because the changes in gravity are so small (a few parts per billion), it requires highly sensitive surveying equipment and data analysis methods to accurately determine what is causing the negative gravity anomaly (Wendling, 2012). A case study involving the development of a business park in southwest Kentucky utilized microgravity surveying to detect potential karst features. Because the site area was so large, typical borehole analysis was not time or cost efficient. Engineers instead used microgravity surveying across the 900 acres. Figure 10 represents one of the gravity readings taken along a roadway:

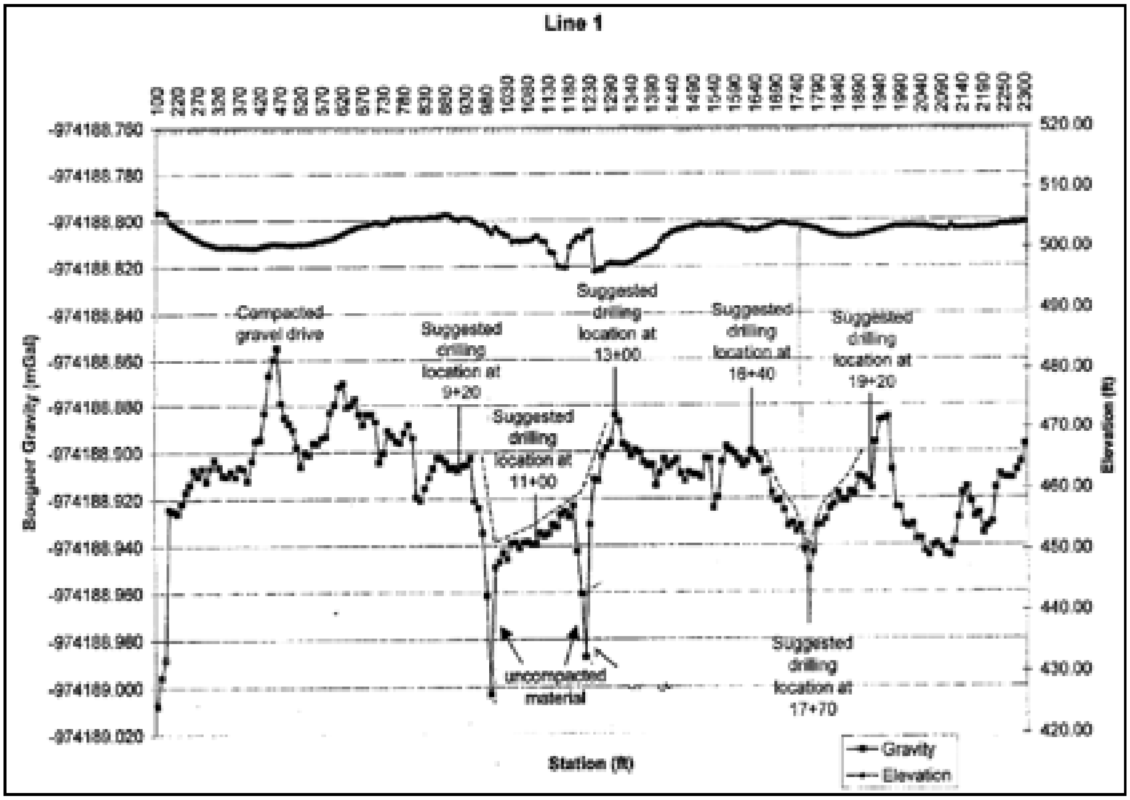

Figure 9. Microgravity Survey.

As one can see in the figure, several bowl shaped negative gravity anomalies were detected, which upon further borehole investigation were attributed to soft, wet, or loose soils which is a possible future sinkhole location (Karem and Ealey, 2008). The peaks in the gravity readings are due to higher density materials such as compacted gravel. These gravity readings will lead engineers to design a plan for the location of each borehole when conducting the in depth soil survey, rather than grid pattern drilling over the entire site.

Once a sinkhole has been discovered using one of the aforementioned methods, it is important to determine the construction possibilities around or above the sinkhole. In order to do this, it is necessary to determine the ultimate bearing capacity loads for the sinkhole before collapse. In the past, analytical methods such as the limit equilibrium and limit analysis were used, but these methods are not good for determining the upper and lower bounds for these tests, and it is often difficult to determine which failure mode will occur (Augarde et al., 2003). Instead, computer programs using finite element analysis method are much better for estimating the load capacity for sinkholes. Finite element analysis involves determining a stress field for the lower bound case and a collapse mechanism for the upper bound. These result in large optimization problems, which are solvable using linear and nonlinear programming methods.

Drumm et al. (2005, 2009) have developed a stability chart for the collapse of residual soil in karst (Figure 10) that could be used to determine the likelihood of collapse based on a numerical analysis of the void based on the dome diameter, overburden height, and soil friction angle. This method could be used to estimate the stability of a site based on an expected overburden thickness and a likely range of anticipated soil void diameters.

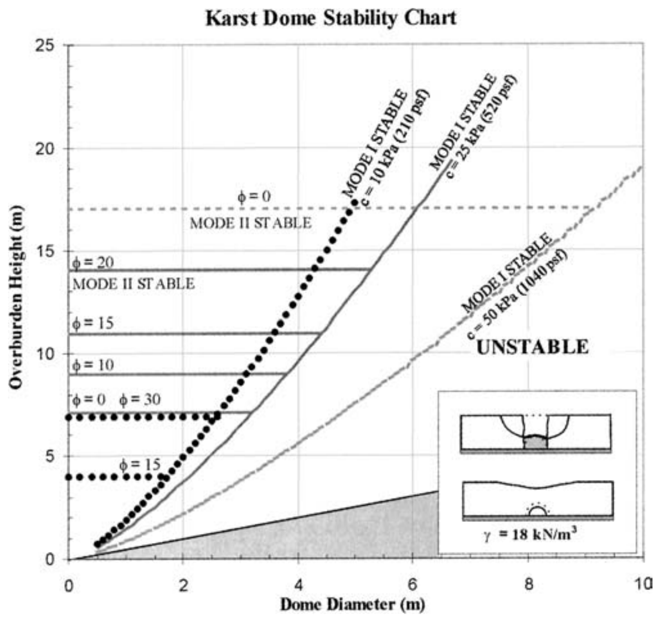

Figure 10. Karst Stability Screening Chart (Drumm, EC and Yang, 2005).

Construction Methods

The following karst construction mitigation methods were examined:

- Excavation and Plugging
- High/Low Mobility Grouting
- Void-Bridging
- Drainage Control

A review of the literature has shown four main practices already used when construction over karst is necessary. These are: excavation and plugging, high or low mobility grouting, void bridging, and drainage control. Due to site variability and geotechnical approximations, it is rare for a single practice to be used in the field, and most engineers choose a combination of methods to overcome soil weakness due to soils voids. Pre-collapsing and/or high-impact compaction can also be useful techniques, especially when working with shallow or already weakened soil overburden (the roof of soil voids). These techniques, however, are not included in the four practices primarily because, unlike the others, they can rarely be used as stand-alone means for overcoming karst (Sowers, 1996). It should be noted that these methods would not necessarily be useful for the construction of bridge piers within karst terrain. For construction of this type, it is more advantageous to vary the type of footings installed instead of trying to fix the void itself. Spread footings (for stable overburdens), driven piles, and caissons have all provided sound foundations for bridge piers in karst terrain (Qubain et al., 1998). It is also worth noting that the term “construction methods” can often be used interchangeably with “remedial measures”; the difference lies only in the end purpose of these technologies, but not in their application.

Excavation and Plugging

Excavation and plugging is one of the most commonly used techniques in the field. This technique is best suited for shallow sinkholes up to 15ft deep (Lail, 2012), and should not be used in deeper sinkholes due to stability concerns and the possibility of collapse. It is important, therefore, to have a reasonable understanding of the specific void geometries of the intended site before the method is selected. This process involves the removal of all soil, rock, and debris within the weak zones, “capping” the throats of the soil voids, and backfilling/compacting to desired densities for further construction (Fig. 12).

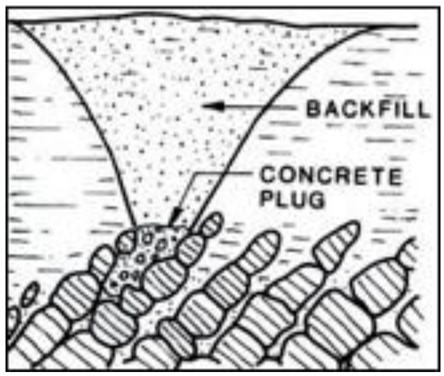

Figure 11. Excavation and Plugging (Sowers, 1996).

The gaps between the limestone (i.e. void throats) should be filled with concrete or grout, but in some cases may be a rock fill plug (stone plug with a sand cement mortar on top). Some experts suggest the most secure plug comes from placing concrete at least 1.5 times deeper than the width of the throat (Sowers, 1996). One approach to this method is to apply an inverted filter to the weakened zone. Based on Karl Terzaghi’s 1939 empirical filter criteria, it entails placing large enough rocks or boulders at the bottom of the excavation, with courses of progressively finer rock and gravel placed and compacted above the base course (Ralstein and Oweis, 1999). This approach to the method should not be used for sites where the soil strength needs to be greatly improved, but one benefit is that it acts as a natural filter to underlying hydraulic features. Depending on the site, sump pumps and/or wells can be used to monitor and control groundwater levels during excavation.

High/Low Mobility Grouting

The second practice for sinkhole stabilization is to drill down until the karst voids are reached, pump high or low mobility grout (HMG/LMG) into the soil until it reaches a specified pressure, then (depending on subsurface topography), raise the pumping mechanism and repeat. A good example of where this worked well was during reconstruction of a highway ramp in King of Prussia, Pennsylvania, where grout was placed at 10ft centers and 2ft stages (vertically) in order to increase soil strength throughout, resulting in acceptable soil parameters for ramp construction. (Petersen et al., 2004). Grout is pumped in a grid pattern over the site, unless only singular, large voids are present that can be treated as isolated sinkholes. HMG is generally used for areas with larger, distinct voids (Fig. 13), so the grout has adequate viscosity and fills up the voids, whereas LMG is better suited for smaller, more dispersed voids in the subsurface, and is usually placed in columns, as in the Pennsylvania example.

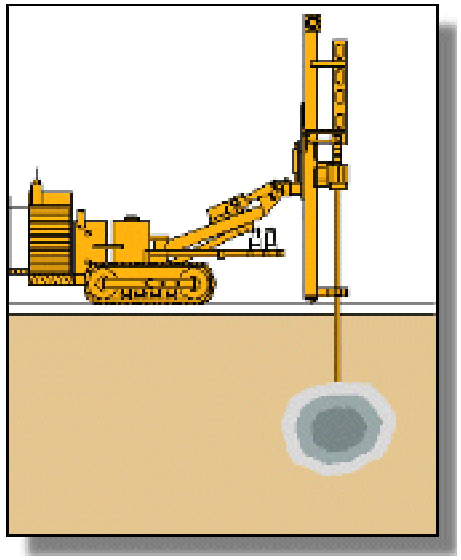

Figure 12. Soil Grouting (Johansson, 2000).

Generally, a 1-3 inch slump is defined as LMG whereas HMG will be anything over a 3-inch slump. Typical pressures of compaction grouting are from 250 to 500 psi (Sowers, 1996). The economic constraints of the project must also be taken into consideration when deciding between HMG and LMG, with HMG being easier to pump and costing less per cubic yard, but possibly filling in extraneous voids that may not actually need stabilization (Casey et al., 2004). Normal costs for the grout alone range from $300 - $400 per cubic yard. Grouting is a more acceptable way to repair soil stability than simply excavating and plugging, especially if the structure to be built on top of the soil is significantly heavy.

Void-Bridging

Void-bridging is a third practice that is used extensively when sinkholes due to karst terrain are discovered, but has more limited uses than both excavation/plugging and grouting techniques. In this method, a high-strength geotextile material such as a polyethylene terephthalate (PET), polypropylene (PP), or polyethylene carbonate (PEC) composite, woven into a mesh, is placed over the potential voids in order to increase the load carrying capacity of the overburden above it and break up shear failure planes (Tencate, 2012). In case of embankments, this allows for a higher construction and steeper side slopes than would otherwise be possible (Fig. 13).

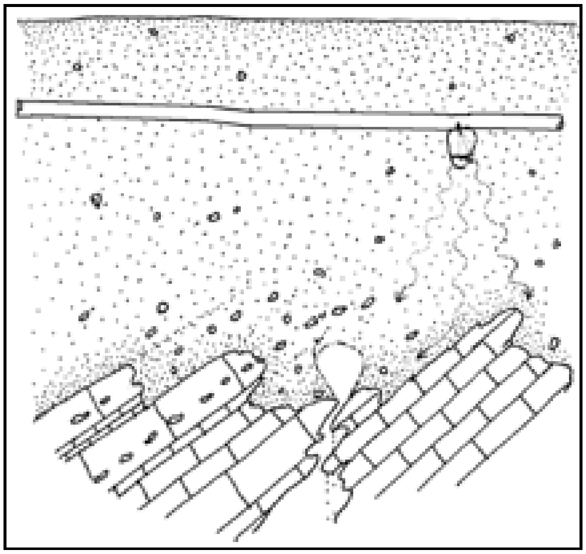

Figure 13. Void Bridging (Maciolek, 2005).

Void-bridging, however, is only recommended for use underneath lightweight structures such as highways, railways, or instances where the height of the cover fill is not that deep. Several analytical methods are available for design: British Standards Institution 1995 (BS 8006); Villard et al. (2000, 2002). Though there have been some instances of void-bridging used under larger, heavier projects, this should only be done if all other factors mandate it, and only under strict supervision of experienced geotechnical engineers (Sowers, 1996). In addition, void bridging is not recommended for use in projects with large cavity diameters (4 m) (Gourc et al., 1999). Though in the case of large diameters or heavy loading, one of the greatest benefits of using high-strength is that it can (and should) be designed to allow for enough measurable strain to occur before a catastrophic failure happens (Bonaparte and Berg, 1987). Whether monitored by strain gages, sensors that measure changes in contact pressures between the geotextile mat and the soil, or the deformation is simply visible, this design ensures that remedial measures can be taken before an extreme event takes place. Often this method is used to create a barrier through which the top layer of sand and other soils cannot pass, and is emplaced during the penultimate construction phase of an excavation and plugging method.

Drainage Control Measures

The final practice of construction over karst topography, which is crucial to the site's long-term stability and potential for ongoing void creation, is proper drainage control. It is well recognized that hydraulic flow, to include changes in groundwater levels and vertical seepage, especially from extreme weather events, is a critical factor in sinkhole formation in karst terrain (Petersen et al., 2004). The infiltration of surface water through the overburden "soaks the low-plasticity soil and the groundwater flowing in the bedrock crevices gradually washes away the fine-grain material" (Yang et al., 2006). This diminishes the strength of the soil and eventually can lead to soil voids, an overburden stability system called "the arch effect" (Drumm, E et al., 2009), and cover collapse of the weakened overburden. In addition to this, the human impacts of actually excavating the soil in order to improve the karst can dramatically aggravate the problem, as the overburden is cut away and rainwater now has direct access to the exposed bedrock. During construction, the potential for large hydraulic gradients combined with highly erodible soil creates an environment conducive to sinkhole formation (Petersen et al., 2004). Combatting this exposure, both during construction, and after project completion is a major concern and is generally achieved in at least one of two ways: lining drainage routes and storm water detention areas with high-density polyethylene (HDPE) or geocomposite clay liners (GCL), and sealing all joints in subsurface drainage pipes (Fig. 14) (Maciolek, 2005).

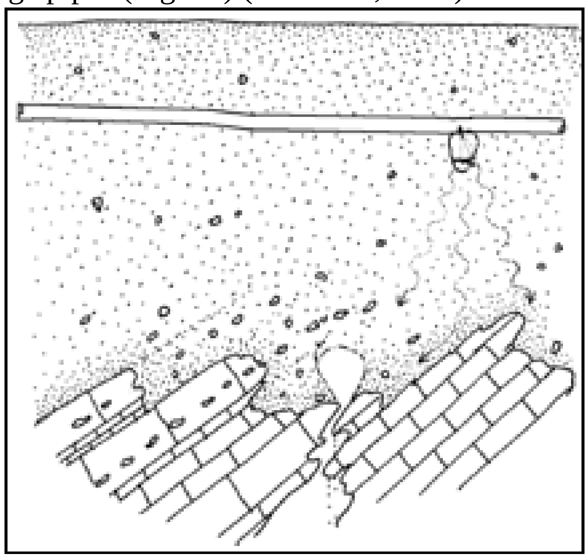

Figure 14. Karst Mitigation Techniques (Maciolek, 2005).

Additional "proactive" drainage measures can be employed as well, such as the use of "graded rock pads, overflow channels from sinkholes to free-draining areas, sinkhole opening improvement and protection, and curbs for embankment sections" (Moore, 2006). The main goal of these methods is to effectively control the entry points of surface runoff and divert subsurface water away from known sinkholes which, state guidelines note, should under no circumstance be used as a means for drainage purposes (Commonwealth of Kentucky Transportation Cabinet, 2005). This prescription is, of course, even more relevant in areas with an unusually high percentage of karst terrain, such as those on Virginia's northwestern boundary (Fig. 15).

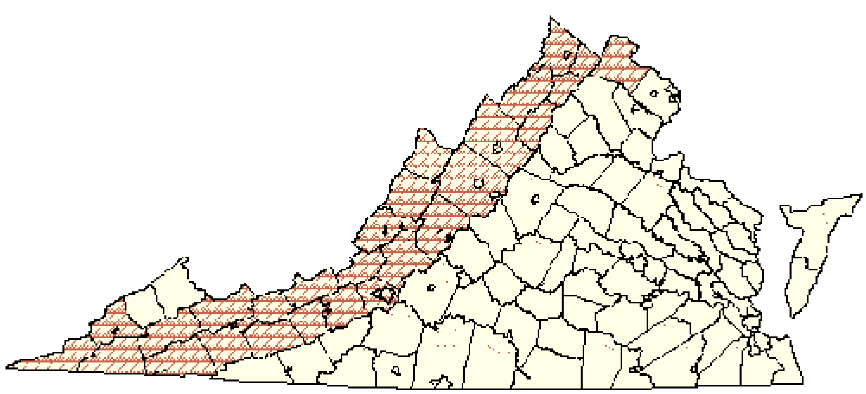

Figure 15. Virginia Karst Map (Orndorff, 2013).

CURRENT VDOT PRACTICE

Currently, there are no specific guidelines regarding karst within VDOT standards. Karst is usually dealt with on a case-by-case basis with the input of the District Materials Engineer and

Geologist. While not a “standard” practice, the most frequently used construction mitigation method

SOME EXISTING GUIDELINES AND SPECIFICATIONS

Kentucky has it’s own set of guidelines for the treatment of open sinkholes. Since the two states have similar geologies with respect to karst, VDOT might consider using some of its techniques in the future. The figure below displays the remediation method for one of six conditions - Soil embankment over deep overburden with open sinkholes:

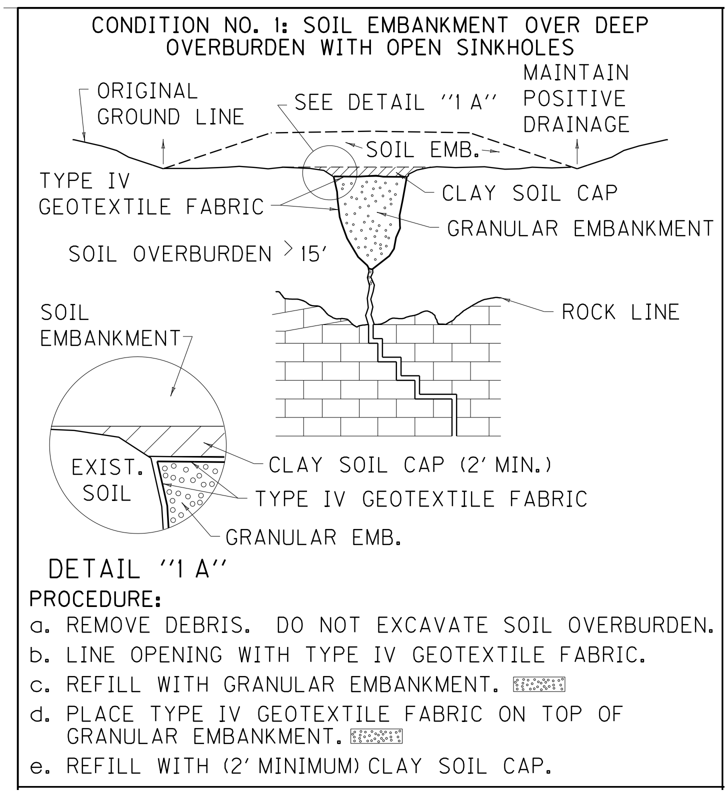

Figure 16. Sinkhole Remediation Graphic (Galed, 1999).

The other major guideline that is most commonly reference is the British Standard BS_8006: Code of practice for strengthened/reinforced soils, which gives guidance in the stabilization of soils using

SUMMARY OF FINDINGS

Through the review of the literature and the investigation into practices in other states, it has been determined that each karstic site (or possible karstic site) must be treated within its own right – that is, there is no “tried-and-true” method either for the noninvasive detection methods, or construction techniques that will work with all sites. Therefore it is difficult to prescribe any standard procedure to follow when karst terrain is encountered. However, the literature review of relevant material has afforded a few key messages based on reoccurring themes.

Karst is a very volatile feature, and as we have seen, initial problems can be made far worse by negligence in design, implementation of building techniques, and even long-term planning measures. A comprehensive understanding of the site must therefore be gained before these critical decisions are made; the entire subsurface may play a part in soil stability and sinkhole interaction. Wherever possible, the design engineer of a karstic site project should make every effort to preempt and avoid high-risk events such as overburden strength reductions and excessive water infiltration, especially in an environment conducive to large hydraulic gradients (such as heavy precipitation after a long drought) (Yang et al., 2006).

These areas are often very dynamic and environmentally sensitive. Proactive measures, then, are much more necessary than reactive ones when karst is present during construction – and it seems better to err on the side of caution and preempt adverse conditions such as high levels of precipitation with methods such as drainage control. On an economic basis, even though up-front cost may be greater, preventative measures can act as insurance against the events where sinkhole formations have been aggravated and the “cost for each incremental gain...of sinkhole prevention [is] staggering” (Petersen et al., 2004).

There is a synergistic relationship between the circulation of water and the dissolution of rock (LaMoreaux, 1998). As a result, with formations exposed, drastic changes can occur within a relatively short period of time. Another of these preemptive measures, therefore, might be to minimize foundation construction times when operating in these environments. In some instances, the most suitable “proactive approach” may even be to relocate the proposed site entirely, as the Tennessee Department of Transportation has often experienced (Moore, 2006).

DISCUSSION

The attempt to create a catalogue of construction projects in karst hazards began with a conversation with Chaz Weaver, the Materials Engineer and Brian Bruckno, Engineering Geologist both of the Staunton District. The Staunton District has had various projects in karst terrain and considers it a significant problem. From this discussion, it was mentioned that one possible way for identifying karst in past construction projects was to overlay the USGS karst map with a GIS file of past VDOT projects and compare the areas. However, it was noted that, just because a project was in an area considered karstic, the project itself might not have necessarily encountered voids within the construction. Therefore, it would be necessary to check the records of every single project within the karst area for evidence of karst. Upon inspection, this included well over one hundred projects. After this revelation, it was decided by the author to reduce down the projects for the karst catalogue to a much smaller data set by including only projects with known karst occurrences.

As a starting point for this smaller data set, Chaz Weaver provided a personal list of projects in the Staunton District in which significant problems had been encountered due to karst since 2010. This list Mr. Weaver had begun to keep himself for his own personal use as a reference to jobs in which karst mitigation methods were employed. No metadata notation of karst was recorded for each of these instances and was only noted within the reports themselves. Investigation of the personal list found that actually finding known instances of karst within the project reports was particularly problematic first and foremost because it was difficult to search lengthy reports (many of which were not electronic) for particular instances without recorded dates. In addition, contractors also mistakenly misidentify scour and drainage issues as karst.

Interestingly enough, during the author's investigation into previous projects, it was discovered Audrey Moruza of VCTIR, for a project unrelated to the current project, was also seeking information on past VDOT projects involving karst. After a discussion about the difficulty of retrieving data, it was decided that a list of projects numbers where karst was an issue might be able to be obtained through interviews with Materials engineers in various districts. It was agreed that the author would accompany Ms. Moruza on some of these interviews and help to begin a database. Since it is evident that construction method / cost estimation for projects involving karst is information valuable for current and future research, it is the recommendation of the author that VDOT create a policy that when karst is encountered in a project, some sort of document must be submitted that summarizes the occurrence of the karst, the construction method applied, and enough dates/specifics that would allow someone to be able to trace how the situation was handled through the project report.

CONCLUSIONS

- Proper site investigation prior to construction in karst prone regions is extremely valuable in determining the location of possible voids. Site investigations should include preliminary studies, reconnaissance surveys, and field investigations using geophysical techniques, sample borings, and soundings (Adams and Lovell, 1984).
- Geophysical methods can be applied in identifying sinkholes and voids. However, the type of method chosen will depend on the site soil type and the size of the void to be located. It is recommended that multiple methods be employed or at least one method at multiple angles to properly identify voids below the surface.
- There is not one particular construction method that is most appropriate for dealing with karst. Karst must be dealt with on a case-by-case basis. However, it is agreed upon by many (Sowers, 1996, Adams and Lovell, 1984, Below, 2004, Petersen et al., 2004) that drainage control measures should be implemented within the site. By controlling the drainage, current and future void expansion can be mitigated. Drainage factors that the literature suggests should be examined include: vertical and horizontal seepage, ground water table levels over time, and overland flow patterns.
- Lastly, on a broader scale, issues involving unstable/unsuitable topography must be brought into sharper relief within our education system – not only the technical aspect of the geology, but the legal, ethical, and environmental aspects of land over-development which may cause harm to people, infrastructure, and natural ecosystems. Karst continues to be a relevant topic, and as demand for living space and industrial real estate increases, our geotechnical technologies and the experts who wield them must evolve and develop alongside.

RECOMMENDATIONS

1.) VDOT should begin a documentation processes to identify projects involving karst in a manner that makes the data retrievable for research.

From the current investigation and the on-going investigation into karst projects by Audrey Moruza, the information that seems to be of particular interest concerning karst includes the remediation measures taken by the contractor and the resulting cost of those measures above and beyond the original expected costs.

2.) It is recommended that VDOT conduct additional research into the identification of karst using geophysical or other noninvasive methods.

BENEFITS AND IMPLEMENTION PROSPECTS

If the recommendations within this report were implemented, VDOT would create a means to a sound foundation for future research involving karst. Since karst is a commonly occurring problem, especially in the western part of the state, an improvement in the methodologies used in mitigation would be achievable if it was possible to identify and evaluate strategies previously used. Were VDOT to require documentation of karst within current and future projects, this outcome would be feasible. Since it is evident that construction method / cost estimation for projects involving karst is information valuable for current and future research, it is the recommendation of the author that VDOT create a policy that when karst is encountered in a project, some sort of document must be submitted that summarizes the occurrence of the karst, the construction method applied, and enough dates/specifics that would allow someone to be able to trace how the situation was handled through the project report. Furthermore, it would behoove VDOT to begin this process by interviewing current district managers on projects involving karst, as is the current plan for the project in which Audrey Moruza is involved.

In addition, it was recommended that additional research take place on the identification of karst using geophysical or other noninvasive methods. If sites in areas of known karst are scanned before or during construction, it might be possible to identify possible hazards and alter construction plans or mitigate the areas with grouting before problems arise. Mitigation of karst during construction could also prevent road crews from having to return to job sites after construction and from performing maintenance/repair in karst affect areas. Investigation of geophysical methods of detection is also important because while multiple methods for geophysical detection are available, void sizes and soil type have a significant affect of the success of the detection. This was readily apparent in the literature studied as part of this report. Studies specific to the soil types and void sizes common to Virginia would help to narrow down the most useful technologies for this particular area.

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REFERENCES

Adams, FT, and Lovell, CW. *Geotechnical Engineering Problems in the Karst Region of Southern Indiana.* Joint Transporatiation Research Program, Indiana Department of Transporation and Purdue University. FHWA/IN/JHRP-84/12, West Lafayette, Indiana, 1984.

Anderson, NL. *Assessment of Karst Activity at Springfield Route 60 Study Site.* Kentucky Department of Transportation, 2008.

Augarde, C, Lyamin, A, and Sloan, S. Prediction of Undrained Sinkhole Collapse. *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 129, No. 3, 2003, pp. 197-205.

Batayneh, A, Abueladas, A, and Moumani, K. Use of Ground Penetrating Radar for Assessment of Potential Sinkhole Conditions: An Example from Ghor al Haditha Area, Jordan. *Environmental Geology,* Vol. 41, No. 8, 2002, pp. 977-983.

Below, M. Environmental Hazards in Karst Landscapes. 2004. http://www.uwec.edu/jolhm/eh/below/Matt%20Below%20-%20GEOG%20361-WHAT%20IS%20KARST.htm. Accessed November 4, 2012.

Bonaparte, R, and Berg, RR. The use of geosynthetics to upport roadways over sinkhole prone areas. 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karst, Orlando, FL, 1987, pp. 437-445.

British Standards Institution. Code of Practice for strengthened reinforced soils and other fills. London, 1995.

Casey, T, Wright, W, Lockman, G, and Lin, G. Sinkhole Repair Under Highway Embankments *Geotechnical Engineering for Transportation Projects,* Vol., 2004, pp. 1840-1847.

Commonwealth of Kentucky Transportation Cabinet. *Geotechnical Guidance Manual*. Organizational Management Branch, 2005. http://transportation.ky.gov/ organizational-resources/policy%20manuals%20library/geotechnical.pdf Accessed October 25, 2012.

Drumm, E, Akturk, O, Akgun, H, and Tutlouglu, L. Stability Charts for the Collapse of Residual Soil in Karst. *Journal of Geotechnical and Geoenvironmental Engineering,* Vol., 2009, pp. 925-931.

Drumm, E, and Yang, M. Preliminary Screening of Residual Soil Stability in Karst Terrain. *Environmental & Engineering Geoscience,* Vol. 11, No. 1, 2005, pp. 29-42.

El-Qady, G, Hafez, M, Abdalla, M, and Ushijima, K. Imaging Subsurface Cavities Using Geoelectric Tomography and Ground-Penetrating Radar. *Journal of Cave Studies,* Vol. 67, No. 3, 2005, pp. 174-181.

Environmental Science Institute. The Features of a Karst System. University of Texas at Austin, 2012 http://www.esi.utexas.edu/outreach/caves/karst.php. Accessed May 3, 2013.

Enviroscan. Seismic Refraction Geometry. 2003 http://www.enviroscan.com/html/seismic_refraction_versus_refl.html. Accessed November 20, 2012.

Epstein, J, Weary, D, Orndorff, R, Bailey, Z, and Kerbo, R. National Karst Map. Reston, VA: USGS, 2002 http://water.usgs.gov/ogw/karst/kig2002/jbe_map.html. Accessed October 15, 2012.

Galed, W. Treatment of Open Sinkholes. Frankfort, KY: Kentucky Department of Highways, 1999.

Gourc, JP, Villard, P, Giraud, H, Blivet, JC, Khay, M, Imbert, B, Morbois, A, and Delmas, P. Sinkholes Beneath a Reinforced Earthfill: A Large-scale Motorway and Railway Experiment. *Geosynthetics,* Vol., 1999, pp. 833-846.

Harper, D. Online Etymology Dictionary. 2012. http://www.etymonline.com/index.php?allowed_in_frame=0&search=karst&searchmode=none. Accessed November 19, 2012.

Harrison, H, and Hiltunen, D. Characterization of Karst Terrain via SASW Seismic Wave method. 2004.

Hiltunen, D, and Cramer, B. Application of Seismic Refraction Tomography in Karst Terrane. *Journal of Geotechnical and Geoenvironmental Engineering,* Vol. 134, No. 7, 2008, pp. 938-948.

Johansson, J. Soil Grouting Figure. Seattle, WA: University of Washington, 2000 http://www.ce.washington.edu/~liquefaction/html/how/soilimprovement.html. Accessed December 5, 2012.

Karem, W, and Ealey, B. "Development of a Business Park in Karst Terrain." *ASCE*, 2008

Lail, J. *Treatment of Open Sinkholes.* Kentucky Department of Highways, 2012, http://transportation.ky.gov/Highway-Design/Standard%20Drawings%20%20Sepias%20PDFs%202012/Sepia%20003.pdf. Accessed December 5, 2012.

LaMoreaux, P. "A History of Karst Studies: From Stone Age to the Present." *Focus*, 1998, pp. 22

Maciolek, D. Grouting Program to Stop Flow through Karstic Limestone: A Major Case History. Paper presented at the Sinkholes and the Engineering and Environmental Impacts of Karst: Proceedings of the Tenth Multidisciplinary Conference, San Antonio, TX, 2005.

Missouri Transportation Institute. *Assessment of Karst Activity at Construction Sites Using the Electrical Resistivity Method*. OR07.003, Missouri Department of Transportation, Jefferson City, MO: Missouri Department of Transportation, 2006. http://library.modot.mo.gov/RDT/reports/Ri05049/or07003.pdf. Accessed November 12, 2012.

Moore, H. A Proactive Approach to Planning and Designing Highways in East Tennessee Karst. *Environmental & Engineering Geoscience,* Vol. 12, No. 2, 2006, pp. 147-160.

NJGWS. Diagram Illustrating components of a GPR Survey. New Jersey Department of Environmental Protection,, 2012 http://www.state.nj.us/dep/njgs/geophys/em.htm. Accessed November 22, 2012.

Orndorff, W. VA Counties Containing Karst Topography. Richmond, VA: Virginia Department of Conservation and Recreation, 2013 http://www.dcr.virginia.gov/natural_heritage/karsthome.shtml. Accessed August 1, 2013.

Petersen, W, Meyers, J, and Mackey, R. Sinkhole Remediation Measures for a Highway in King of Prussia Pennsylvania. Sinkholes and the Engineering and Environmental Imapcts of Karst, 2004, pp. 569-579.

Qubain, B, Seksinsky, E, and Li, J. Design Considerations for Bridge Foundations in Karst Terrain. 49th Highway Geology Symposium: Proceedings & Field Trip Guide, Prescott, AZ, 1998, pp. 339-349.

Ralstein, M, and Oweis, I. Geotechnical Engineering Considerations for Stormwater Management in Karst Terrain. Southeastern Pennsylvania Stormwater Management Symposium, 1999 http://www.converseconsultants.com/publications/1999-3_paper.pdf. Accessed October 20, 2012.

Roth, M, Mackey, J, Mackey, C, and Nyquist, J. A Case Study of the Reliability of Multielectrode Earth Resistivity Testing for Geotechnical Investigations in Karst Terrains. *Engineering Geology,* Vol. 65, No. 2, 2002, pp. 225-232.

Roth, M, and Nyquist, J. Evaluation of Multi-Electrode Earth Resistivity. *Geotechnical Testing Journal,* Vol. 26, No. 2, 2003, pp. 12.

Shokouhi, P, Gucunski, N, and Maher, A. Application of Wavelets in Detection of Cavities Under Pavements by Surface Waves. *Transportation Research Record: Journal of the Transportation Research Board,* Vol. 1860, No. 1, 2003, pp. 57-65.

Sowers, G. *Building on Sinkholes: Design and Construction of Foundations in Karst Terrain*. New York, NY: ASCE Press, 1996.

Tallini, M, Gasbarri, D, Ranalli, D, and Scozzafava, M. Investigating Epikarst Using Low-Frequency GPR: Example from the Gran Sasso Range (Central Italy). *Bulletin of Engineering Geology and the Environment,* Vol. 65, No. 4, 2006, pp. 435-443.

Tencate. Reinforced Soil Case Studies. 2012. http://www.tencate.com/flippingbook/publicaties/TenCate%20Soil%20Reinforcement%20Case%20Studies/files/assets/downloads/publication.pdf. Accessed October 22, 2012.

Van Schoor, M. Detection of Sinkholes Using 2D Electrical Resistivity Imaging. *Journal of Applied Geophysics,* Vol. 50, No. 4, 2002, pp. 393-399.

Veni, G. Living with Karst: A Fragile Foundation. 2001.

Villard, P, Gourc, JP, and Bilvet, JC. Risk due to the appearance of localised sinkholes over underground cavities : a geosynthetic preventive reinforcement solution for roads and railways embankments. *French Geotechnical Journal,* Vol. 99, 2002, pp. 23-34.

Villard, P, Gourc, JP, and Giraud, H. A geosynthetic reinforcement solution to prevent the formation of localized sinkholes. *Canadian Geotechnical Journal,* Vol. 37, No. 5, 2000, pp. 987-999.

Wendling, S. ARM Geophysics - Service Microgravity Surveying. 2012. http://www.armgeophysics.net/Services. Accessed December 15, 2012.

Yang, M, Sajedi, D, and Drumm, E. Design and Construction of Highway Structures in Karst Terrain. Paper presented at the Underground Construction and Ground Movement: GeoShanghai, Shanghai, China, June 6-8 2006.

Zhou, W, Beck, BF, and Adams, A. Effective Electrode Array in Mapping Karst hazards in Electrical Resistivity Tomography. *Environmental Geology,* Vol. 42, No. 8, 2002, pp. 922-928.

Zhou, W, Beck, BF, and Stephenson, JB. Reliability of dipole-dipole electrical resistivity tomography for defining depth to bedrock in covered karst terranes. *Environmental Geology,* Vol. 39, No. 7, 2000, pp. 760-766.