METHODS USED TO CARRY OUT SIX ROADWAY INVESTIGATIONS OF SINKHOLES

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ABSTRACT

Karst conditions are a prevalent problem impacting many roads, bridges and highways of the United States. Six case-histories present an overview of investigations made to determine the presence of karst (sinkholes and cavities) and their possible impact on existing or new construction. These six case-histories represent projects which range from reconnaissance investigations to identify possible areas of karst, to detailed investigations including follow-up drilling and remediation considerations. They also cover a wide range of scale (dimensions) of roadway problems.

Each of the six investigations utilized a wide range of data including aerial photos, surface geophysical measurements (on water as well as on land), drilling and geophysical logging. The selection of the methods for each of the unique site conditions is presented, including the parameters measured, the depth of measurements, the site coverage and how the data provide information on subsurface conditions.

In each investigation, the non-intrusive geophysical data provide an assessment of the subsurface conditions that, when integrated with other data, allow the pieces of the puzzle to be brought together in an accurate conceptual model of subsurface karst conditions. The results of this integrated information provided the highway design engineers with the necessary data for developing design and remediation strategies.

PART I
A BRIEF SUMMARY OF SIX ROADWAY INVESTIGATIONS IN KARST

Introduction

This paper contains two parts. Part I provides an overview of the geophysical measurements made as part of the six roadway investigations in karst. Part II provides an expanded discussion of two of the six case-histories using these strategies.

The six case-histories include:

- A detailed emergency investigation of localized subsidence over 1,000 feet on U.S. 27 for Florida DOT;
- A reconnaissance investigation of localized subsidence over 1600 feet of Interstate 24 median for Tennessee DOT;
- A reconnaissance investigation of karst conditions over 4.2 miles of Route 340 for Virginia DOT prior to final design of roadway expansion;
- A reconnaissance and detailed investigation to define areas of karst susceptibly over 7,000 feet of I-70 for Maryland DOT to plan long-term maintenance (Benson, et al, 1998a, 1998b);
- A reconnaissance and detailed investigation of a localized area of about one acre for Federal Bureau of Prisons prior to design (Daniel et al., 1999); and
- A reconnaissance investigation for Florida DOT with follow-up detailed investigation along 8,000 feet of U.S. 1 for a new bridge over water (Benson, et al., 1995a, 1195b).

While all six of the sites are in karst environments: three are associated with present sinkhole activity, two are in areas with historic karst but no recent activity, and one is in an area of no known karst activity. Details of three of the investigations including the geologic setting, the strategy used and the results, are provided in the referenced papers.

Table I summarizes the nature and scale of each project. The size of the sites range from a few acres to 4.2 miles of roadway. Tables II through VII summarize the non-intrusive geophysical methods used on each project and their purpose. Table VIII summarizes the results of the investigations.

Table I – Summary of six karst investigations

Site	Client	Reconnaissance	Detail	Area/Length	Condition
U.S. 27	Florida DOT		X	1,000 feet	Sinkhole activity
I-24	Tennessee DOT	X		1,600 feet	Sinkhole activity
Route 340	Virginia DOT	X		4.2 miles	Historic karst present
I-70	Maryland DOT	X	X	7,000 feet	Sinkhole activity
Virginia Prison	Federal Bureau of Prison	X	X	few acres	Historic karst activity
U.S. 1	Florida DOT	X	X	8,000 feet	Unknown karst activity

U.S. 27 (Florida DOT)

Technos responded to an emergency call from the Florida Department of Transportation to provide an assessment of sinkhole collapse on US Highway 27 in Sebring, Florida. An estimated 200 cubic yards of material had been lost, resulting in about 2 feet of subsidence over a portion of the northbound lanes. Subsidence was centered around a surface water drainage system. During the week prior to subsidence, repairs had been made to an area about 500 feet to the south. There are two possible causes of subsidence at this location: one is due to flushing of sand into a surface water drainage structure; another is due to a deep seated cause of collapse associated with karst conditions within rock at a depth of more than 250 feet.

Table II lists the geophysical measurements made at this site and Figure 1 shows their depth of investigation.

Table II – A detailed investigation of 1,000 feet, Florida DOT

Method	Measured Parameter	Station Spacing	Provides
EM31	Electrical conductivity to a depth of 20 feet	Continuous	Identification of variations in shallow strata
Microgravity	Density to a depth of more than a few 100 feet	20 to 40 foot	Identification of zones of low density due to subsidence exist at depth
Resistivity	Electrical resistivity to a depth of 100 feet	20-foot electrode spacing	Detailed characterization of lateral and vertical changes in unconsolidated material
Ground penetrating radar	Dielectric constant to a depth of 10 to 15 feet	Continuous	Shallow indications of soil piping

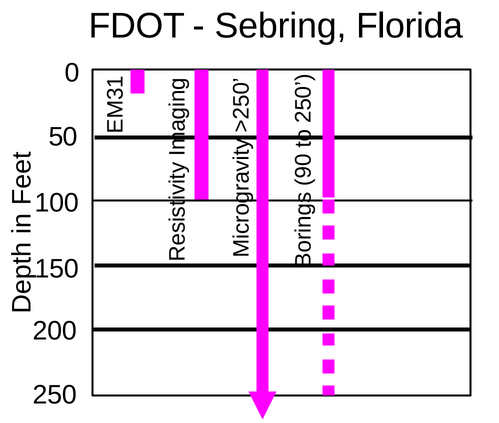

Figure 1

I-24 (Tennessee DOT)

A section of Interstate 24 south of Nashville had recently underwent construction. After construction, a section of the median experienced localized sinkholes with subsidence cracks extending out to the edge of the shoulders within the median. The Tennessee Department of Transportation contracted with Technos, Inc. to conduct a karst investigation of the site. This investigation identified areas of deeper weathered rock associated with regional lineaments. These areas had become active due to diversion and concentration of surface water runoff. Technos responded to a request from TN-DOT to identify the cause of the problem.

Table III lists the geophysical measurements made at this site and Figure 2 shows their depth of investigation.

Table III – A reconnaissance investigation for Tennessee DOT

Method	Measured Parameter	Station Spacing	Provides
2D Resistivity	Resistivity to a depth of 80 feet	20-foot electrode spacing	Map of top of rock, Identification of highly weathered zones
Ground Penetrating Radar	Dielectric constant, to a depth less than 10 feet	Continuous	Shallow indications of soil piping
EM31	Electrical conductivity to a depth of 20 feet	Continuous	Identification of variations in soil conditions and top of rock

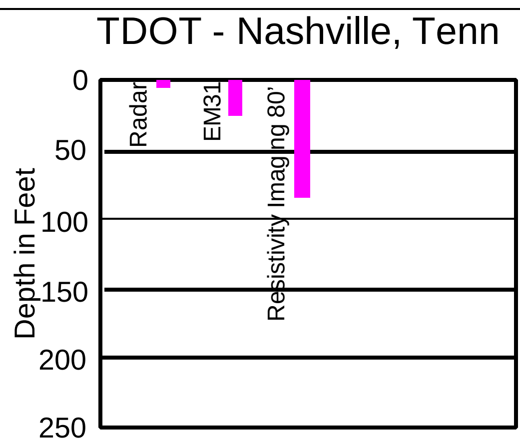

Figure 2

Route 340 (Virginia DOT)

Route 340 is a two lane road that runs along the eastern side of the South Fork of the Shenandoah River in northwestern Virginia. Four bridge replacements and associated road improvements are planned over 4.2 miles. Numerous sinkholes and caves are present along the route. A reconnaissance investigation was carried out to characterize the geology and thickness of soil cover (cutter and pinnacles), and to identify possible karst conditions (highly weathered and fractured rock, sinkholes and cavities). These data were used to design a detailed drilling program.

Table IV lists the geophysical measurements made at this site and Figure 3 shows their depth of investigation.

Table IV – A reconnaissance investigation of 4.2 miles, Virginia DOT

Method	Measured Parameter	Station Spacing	Provides
EM31	Electrical conductivity to a depth of 20 feet	Continuous	Identification of variations in depth of rock and weathered zones
EM34	Electrical conductivity to a depth of 50 feet	Continuous	Identification of variations in depth of rock and weathered zones
2D Resistivity Imaging	Electrical resistivity to a depth of 100 feet	20-foot electrode spacing	Detailed characterization of fractured and weathered zones in rock

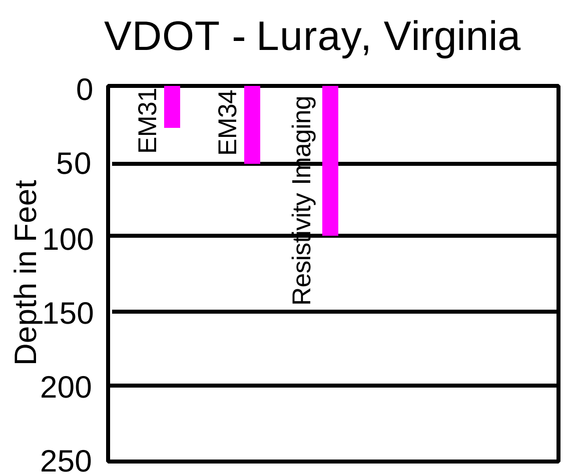

Figure 3

I-70 (Maryland DOT)

A significant number of sinkholes had opened up along I-70 and nearby roadways south of the city of Frederick, Maryland. Extensive emergency grouting was undertaken at certain locations along I-70 in an effort to remediate the problem. A karst investigation was carried out to assess subsurface conditions along 7,000 feet of highway to locate areas in which potential collapse may be concentrated. The results clearly identified two zones which were highly prone to sinkholes development (Benson, et al, 1998-1999).

Table V lists the geophysical measurements made at this site and Figure 4 shows their depth of investigation.

Table V - Maryland DOT

Method	Measured Parameter	Station Spacing	Provides
EM31	Electrical conductivity to a depth of 20 feet	Continuous	Identification of variations in depth of rock
EM34	Electrical conductivity to a depth of 50 feet	Continuous	Identification of variations in depth of rock
Microgravity	Density to a depth of more than 600 feet	15-foot	Identification of zones of low density due to dissolution of limestone (cavities and subsidence)

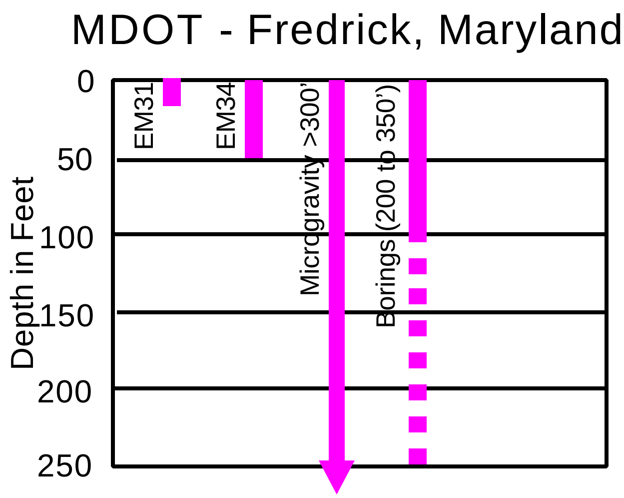

Figure 4

Virginia Prison (Federal Bureau of Prison)

A major federal prison facility was to be constructed in an area of southwestern Virginia, which is a known area of extensive karst development. The main access road to the site along with main utilities for the site cross a “saddle” area between two major coalescing sinkholes. An investigation of subsurface conditions was carried out to evaluate subsurface conditions and to obtain data for site stabilization and construction (Daniel, et al., 1999).

Table VI lists the geophysical measurements made at this site and Figure 5 shows their depth of investigation.

Table VI – Virginia Prison

Method	Parameter Measured	Station Spacing	Provides
EM31	Electrical conductivity to a depth of 20 feet	Continuous	Identification of variations in depth of rock and weathered zones
Microgravity	Density to a depth of more than 100 feet	25- foot	Identification of low density zones due to deeper rock and possible karst zones

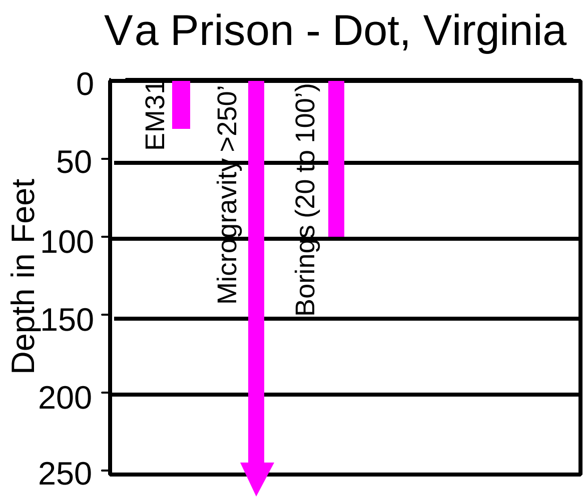

Figure 5

U.S. 1 (Florida DOT)

A high four-lane bridge was planned to replace an existing two-lane draw bridge over Jewfish Creek and Lake Surprise, just north of Key Largo, Florida. Lake Surprise is a shallow circular lake with U.S. 1 passing though its center for about 3,500 feet. Drilled shaft foundations for the bridge will be placed parallel to U.S. 1 over Jewfish Creek and through the center of Lake Surprise. There were a few subtle indications of potential karst in the area. An investigation was carried out to determine if karst conditions existed along the proposed route. The results identified a zone of paleokarst about 1800 feet long where piles for the high portion of the bridge would be placed. These data provided the basis for a cost effective safe design (Benson, et al, 1995a and 1995b).

Table VII lists the geophysical measurements made at this site and Figure 6 shows their depth of investigation.

Table VII - Florida DOT

Method	Measured Parameter	Station Spacing	Provides
Subbottom Profiling (Seismic Reflection)	Acoustic Impedance (velocity and density) to a depth of 200 feet	Continuous	2D stratigraphic cross-sections identify dipping strata
Microgravity	Density to a depth of more than 1,000 feet	25 foot	Identification of low density zones (possible paleokarst zones)
Deep Subbottom Profiling (Seismic Reflection)	Acoustic Impedance (velocity and density) to a depth of 1,000 feet	Continuous	2D stratigraphic cross-sections identify dipping strata
Geophysical Logging	Natural gamma, density and porosity over length of the borehole	Continuous	Details of strata, presence of voids and low density zones

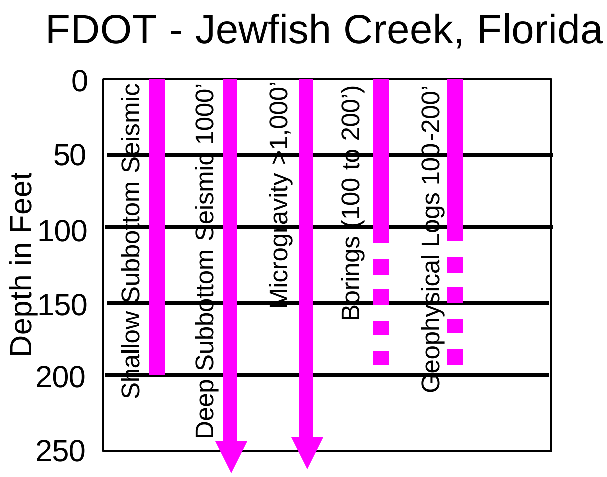

Figure 6

Table VIII summarizes the results of each investigation. In each case, the zone of karst conditions were identified and characterized.

Table VIII – Summary Results of Each Investigation

Site	Conditions	Results
U.S. 27 (Florida DOT)	Sinkhole activity	Results suggest the cause was due to shallow soil piping into a surface water drainage system
I-24(Tennessee DOT)	Sinkhole activity	Results identified weathered zones in rock which were susceptible to subsidence
Route 340 (Virginia DOT)	Historic karst present	Results identified zones of concern
I-70 (Maryland DOT)	Sinkhole activity	Results characterized karst conditions and identified zone of major dissolution of bedrock which were susceptible to subsidence
Virginia Prison (Federal Bureau of Prisons)	Historic karst activity	Results identified a cavity system under the proposed roadway
U.S. 1 (Florida DOT)	Unknown karst activity	Results identified zone of paleo-collapse which would impact bridge foundations

In five cases, some measurements were 20 feet deep or less. In many cases, these reconnaissance measurements were not deep enough to detect the origin of the subsidence problem. However, most subsidence activity is associated with changes in the shallow near surface conditions, which are often readily detected (see papers by Benson and LaFountain (1984) and Benson and Yuhr (1987) which discus near-surface indicators).

Note that EM measurements are commonly used because they are continuous, rapid and easily applied to many situations where data in the upper 20 to 50 feet may be important. Note that 2D resistivity imaging and microgravity are commonly used to obtain deeper data. These deeper measurements are limited in resolution in part by station spacing and are inherently slower than continuous measurements such as EM.

PART II
A REVIEW OF GEOPHYSICAL METHODS USED ON TWO OF THE SIX CASE-HISTORIES

Five key issues will impact the success of karst investigations. They include:

- An assessment of measurable parameters so that measurement methods can be selected that have a reasonable chance of yielding appropriate results within the given geologic environment;
- Consideration of scale issues including the area to be investigated, the size of the expected anomalies, and the volume of our measurement techniques;
- The spatial density of measurements;
- The sequence of work (regional to local and simple to complex); and
- Integration and correlation of the results of measurements from a number of different methods.

The following section discusses how these five issues were incorporated into the site characterization of two highway karst investigations, including: an investigation of karst susceptibly over 7,000 feet of I-70 for Maryland DOT and an investigation of a proposed new bridge along U.S. 1 over 8,000 feet of water for Florida DOT.

EXAMPLE I: SINKHOLES IN I-70, NEAR FREDERICK, MARYLAND
Background

A significant number of sinkholes had opened up along I-70 and nearby roadways south of the city of Frederick, Maryland. Extensive emergency grouting was undertaken at certain locations along I-70 in an effort to remediate the problem. A karst investigation was carried out to assess subsurface conditions along 7,000 feet of highway to locate areas in which potential collapse may be concentrated.

The dewatering of an adjacent quarry was of concern and the area of investigation extended 1200 feet west of the quarry to 2500 feet east of the quarry. The area of investigation also included the boundaries of a major geologic syncline. The issues of concern were an understanding of the geologic setting and its associated karst features (size, depth and causes).

The number of parallel EM survey lines provided continuity of data over the width of this investigation. The parallel lines also provided some redundancy for the fact that some of the EM data would be negatively impacted by metal guard rails and drainage structures.

Measurable Parameters and Depth of Measurements at I-70

The EM method, which measures bulk electrical conductivity, provides a measure of soil thickness and top of rock profile (low conductivity clayey soils in contrast to the unweathered rock high conductivity values). EM31 measurements provide data to a depth of 20 feet and EM34 measurements provide data at a depth of to 50 feet. Since rock was shallow, typically less than 20 feet deep (in unfilled areas based upon existing borings), the EM data were expected to provide a depth of rock profile. This profile was used to identify cutters and pinnacles, and the heavily weathered cutters were identified as more likely areas of sinkhole development.

The gravity measurements provide an indication of changes in density along a survey line. Microgravity was selected to identify low density zones, which would likely be associated with dissolution of limestone and associated cavities and sinkholes. Microgravity data acquired along a survey length of 2,000 feet provides data deeper (600 feet) than the adjacent quarry.

The Scale Issue at I-70

Area

The primary area of concern was centered around the quarry with special emphasis on the area of the original subsidence activity which occurred near the center of the 7,000-foot survey area. The survey was extended beyond this area, so as to also have measurements within background conditions. The geophysical investigation was limited to the road or the adjacent right-of-way.

Size of Expected Anomalies

The individual anomalies were expected to be relatively small based upon known sinkholes (5 to 30-foot diameter) within the unconsolidated material. However, the zone of cavities within the rock would be much broader.

Volume of Measurement

The EM31 responds to shallow changes <20 feet deep, and the measurements integrate a volume of about 30 cubic yards. The EM34 responds to changes <50 feet deep and the measurements integrate a volume of about 800 cubic yards. Microgravity measurements sample to an indefinite depth, sampling an infinite volume; however, shallow changes are easily identified by narrow spatial changes in density.

Spatial Density of Measurements at I-70

Nine parallel EM31 profile lines and five parallel EM34 profile lines provide a reasonable lateral coverage on and to either side of I-70. The EM measurements provide continuous data along parallel profile lines on or adjacent to the road with a measurement every 2 feet along a survey line. A 15-foot station spacing of microgravity measurements provided spatial resolution to resolve individual features less than 50-foot wide.

Sequence of Work at I-70

The work began with regional data and focused upon more detail as the investigation proceeded:

- a review of geologic literature;
- a review of aerial photos;
- a review of existing geotechnical borings;
- a review of existing grouting records;
- detailed foot by foot observations along the entire 7,000 feet of highway and adjacent areas (about 60 acres) with special attention to existing sinkholes;
- a drive on adjacent roads to provide a reconnaissance observations of about 2,500 acres with special attention to other sinkholes;
- a detailed tour and history of the adjacent quarry by the quarry geologist;
- data from surface geophysical measurements, including continuous EM31 and EM34 measurements along with microgravity station measurements were made over 7,000 feet;
- a review and integration of all data and the development of a conceptual model based upon multiple methods;
- follow-up borings to test the conceptual model. Two borings were placed within and two borings outside of karst susceptible areas based upon geophysical data.

Simple to Complex

The focus was upon understanding the geology to provide an insight into karst conditions (considerable effort was expended in becoming familiar with the relevant geologic conditions). The quarry offered an excellent opportunity to observe and focus upon the geology. Finally boring locations were located based upon hard data rather than guesses. The borings were accurately placed within worst-case soil piping and cavity conditions as well as within stable background conditions to further verify the conceptual model. Note that the installation of detailed borings was one of the last steps in the investigation.

Integration of Data From a Variety Measurements at I-70

All of the data listed above (see Regional to Local, Sequence of Work) was first interpreted independently and then integrated to provide an accurate conceptual model of subsurface conditions. The gravity data provided the lateral extent and, by modeling, the vertical extent of the high risk cavernous zones. This was subsequently verified by boring data. The result was that the interpretation of subsurface conditions and the resulting conceptual model had a high level of confidence.

EXAMPLE II: JEWFISH CREEK BRIDGE ALONG U.S. 1 IN THE FLORIDA KEYS

Background

A high, four-lane fixed bridge was planned to replace an existing two-lane draw bridge over Jewfish Creek and Lake Surprise, just north of Key Largo, Florida. Its primary purpose was to provide a means of rapid evacuation from the Florida Keys in case of a hurricane.

Lake Surprise is a shallow circular lake with the present road U.S. 1 passing though its center for about 3,500 feet. Drilled shaft foundations for the bridge will be placed parallel to U.S. 1 over Jewfish Creek and through the center of Lake Surprise. The concern was that the lake may be a sinkhole lake and that bridge foundation piles could be compromised. While sinkhole lakes are common in much of Florida, they are not thought to exist in the Florida Keys.

> A sinkhole lake is formed when the overlying, mostly unconsolidated, materials collapse into an existing cavity within the deeper limestone and form a lake at the surface. The throat is then plugged and the lake becomes stable. Most all lakes in Florida (with the exception of those dug for mining and decorative purposes) are caused by sinkhole collapse.

An investigation was carried out to determine if karst (sinkhole) conditions existed along or near the proposed route. While the primary area of interest was only about 37 acres, over 8,000 feet, the area of reconnaissance investigation was about 20,000 acres. About 55% (11,000 acres) of the area is shallow water, about 44% is impenetrable, mangroves and only 1% or about 20 acres are accessible land including the two-lane road, U.S. 1.

Measured Parameters and Depth of Measurements at Jewfish Creek

Given the setting (only a little accessible land and considerable water access), our choices for surface geophysical methods are limited. Land geophysical measurements were for the most part limited to the existing road U.S. 1. The two-lane road with metal guard rails eliminated the use of EM methods and possibly resistivity measurements.

Since the cause of a sinkhole lake might be a deeper cavity system, we were looking for lower density values associated with dissolution of limestone, cavities, and sinkholes. Microgravity comes closest of all the geophysical methods to allowing a positive statement regarding the presence or absence of subsurface cavities at a site (Butler, 1977). Therefore, microgravity was run along one side of the 2 lane road. To minimize the effects from heavy traffic, gravity measurements were made at night.

The other obvious method for karst characterization was subbottom seismic reflection measurements. Since these measurements are made continuously from a boat, they are very rapid reconnaissance measurements that can also provide considerable detail. These measurements can be used to identify anomalously steeply dipping strata which would identify areas of paleo-collapse. The subbottom profiling (seismic reflection) data could be run parallel to the existing roadway on both sides, along the entire width of Lake Surprise. Subbottom seismic reflection data was used to carry out reconnaissance survey over the extensive waterways surrounding the proposed road. Two different seismic surveys were used. A shallow high resolution survey was run with a 300-joule EG&G uniboom to a depth of about 200 feet. A deeper survey to 1,000 feet was run with a 7,000-joule sparker system.

The Scale Issue at Jewfish Creek

<u>Area</u>

The scale issue at Jewfish Creek was defined by the length of the bridge and its approaches (8,000 feet). This included a possible sinkhole lake through which the bridge was to be constructed.

The primary area of concern was centered around the new road to be built across Lake Surprise and at Jewfish Creek where the highest bridge spans occur. The survey was extended beyond this area (for a total of 8,000 feet) so as to also have measurements within background conditions.

Size of Expected Anomalies

The size of expected individual anomalies was unknown. Paleo-sinkholes throats in lakes range from 10 to 100 feet in diameter or more. However, the zone of deeper cavities within rock would likely be much larger.

Volume of Measurement

Subbottom seismic reflection measurements provide rather high vertical and lateral resolution of strata over a conical area beneath the boat. The volume of measurement and resolution decreases with increasing depth. Microgravity measurements sample to an indefinite depth, sampling an infinite volume; however, shallow changes are easily identified by narrow spatial changes in density.

Spatial Density of Measurements at Jewfish Creek

Since the subbottom data is essentially continuous, data every ½ second at a speed of 3 mph (that's a data point every 2.5 feet), the resulting data were of high lateral density. Subbottom reconnaissance line were run over much of the 600-acre lake (about 10 line miles of data) with emphasis on increased data density parallel to the existing road. Initial reconnaissance lines were widely spaced over 1,100 acres and subsequent lines to define details of an anomaly were spaced 25 feet apart.

Gravity measurements were made at a 25-foot interval, which was more than adequate to define a typical paleo-collapse zone expected. Microgravity data along a survey line of 8,000 feet provides data to depths of more than 1,000 feet. The 25-foot microgravity station spacing provided spatial resolution to resolve individual features as small as 50-foot wide. This station spacing was more than adequate, since we were looking for a larger deeper cavity system which would have lead to a collapse and a sinkhole lake.

Sequence of Work at Jewfish Creek

Regional to Local

The work began with regional data and focused upon more details as the investigation proceeded:

- a review of geologic literature;
- a review of aerial photos and lineament analyses;
- a review of 34 existing geotechnical borings over 8,000 feet (fluid loss and low blow counts);
- a fly-over in a light aircraft to provide an overview of the site specific conditions;
- data from surface geophysical measurements, including continuous subbottom profiling along with microgravity station measurements;
- a review and integration of all data and the development of a conceptual model based upon multiple methods of measurements;
- follow-up borings to test the conceptual model. Three borings were placed within and one boring outside of karst susceptible areas based upon geophysical data;
- geophysical logging.

Simple to Complex

The focus of the investigation was upon understanding the geology to provide an insight to karst conditions.

The project started with a reconnaissance phase along the entire design of 8,000-feet. Since the water area to be investigated was quite large (4,000 feet across), the continuous subbottom data by boat provided a means of economically covering a large area. The initial reconnaissance measurements (microgravity and subbottom profiling) clearly identified a wide 1,500-foot, 100 microGal gravity anomaly along with dipping strata at a location where the piles for the high bridge were to be placed.

Subsequent work focused upon more detailed data using both gravity measurements beyond the road to provide additional data to bound the gravity anomaly and subbottom data with a line spacing of 25 feet to provide contoured data of the paleo-collapse zone.

Finally a boring program was initiated which focused upon the site specific details. Four boring locations were located based upon the detailed subbottom data, rather than guesses. Three borings were accurately placed within worst-case soil piping and cavity conditions and one within stable background conditions to further verify the conceptual model. Finally, geophysical logs were run in the four boreholes to provide stratigraphic data and assess the presence of voids. Note that the borings and geophysical logs (the most detailed data) were one of the last steps of the investigation.

Integration of Data From a Variety Measurements at Jewfish Creek

All of the data listed above (see Sequence of Work, Regional to Local) were first interpreted independently and then integrated to provide an acurate conceptual model of subsurface karst conditions. The results of all methods of measurements indicated the presnece of a sinkhole. Both the gravity and deep seismic data provided an estimate to the depth of the cavity system which caused the sinkhole. Borings and geophysical logs provided indications of shallow voids. The result was that the interpretation of subsurface conditions and the resulting conceptual model had a high level of confidence.

CONCLUSIONS

These six case-histories show that a range of methods must be considered to provide appropriate data to resolve specific project needs such as reconnaissance, or detailed investigations on land or on water. In each case, remote sensing and geophysical measurements play an important roll in reaching an accurate and complete interpretation of subsurface conditions. Many remote sensing, non and minimally invasive methods, as well as traditional boring methods of investigation can be applied to resolve such geotechnical problems. All methods of measurements have advantages and limitations, and there is no single, universally applicable method or group of methods that can be used to meet all project needs. While a given method may be successful in one situation it may not be in another. Although there are many method selection guidelines available, the selection of the appropriate combination of methods can only be arrived at by experienced, hands-on professionals.

Key issues that impact the selection and use of methods include; the scale of the problem and measurements. Other factors include the sequence of work and the use of multiple methods. However, the most critical issue is that of data density. Each step of the way should be focused upon obtaining basic hydrogeologic data with multiple sources of data used to confirm site specific conditions. When measurements by different methods agree, interpretations will have a higher level of confidence, and the impact of the non-uniqueness of each set of geophysical data is reduced.

The major portion of the site characterization effort (including budget) should be focused upon gathering data (Figure 13). While interpretative conclusions and opinions are a necessary and important part of any site characterization, they must be supported in a logical and obvious way by sufficient data which has been tested and proven to be correct. A solid base of data (Figure 14) enables us to carry out subsequent efforts such as modeling, risk assessment and remediation with much greater confidence and accuracy while minimizing uncertainties. The more data we have, the less we rely on assumptions and opinions. In addition, observations by experienced professionals are essential to resolving complex geotechnical problems, such as karst and subsidence.

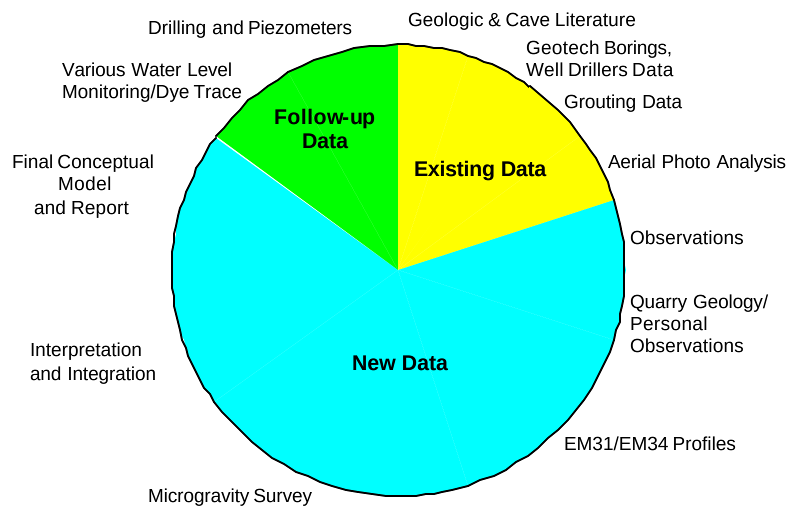

Figure 13. Distribution of Effort at Maryland I-70 Project

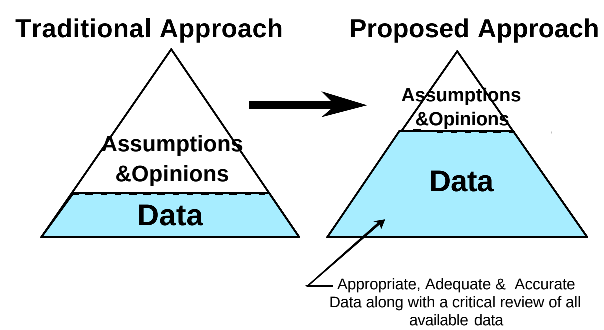

Figure 14. Increasing the data and minimizing assumptions and opinions forms a solid basis for understanding site conditions.

When we finally arrive at a reasonably accurate site characterization, we may look at the result as trivial and obvious. However, the path and effort to reach this point will rarely be easy or straightforward.

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