The Selection and Application of Geophysical Test Methods in West Central Florida Karst Regions

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Abstract

Karst regions present some of the most challenging conditions for design of new and remediation of existing structures. Without the appreciation of the highly variable conditions that often typify karst regions, exponential increases in site development costs can occur both during and after construction. Properly selected and applied geophysical tests can significantly reduce site “unknowns”, allowing for better prediction of costs and better selection of appropriate foundations in the planning stage rather than during and/or after construction. Case studies are given for projects in west-central Florida that have used geophysical tests to provide early information on subsurface conditions and allowed optimization of site use and foundation design.

1. Introduction

This paper provides information and insight to decision makers who are tasked with selecting and designing geophysical investigations for projects in karst regions. Although the case studies discussed herein were sites in West Central Florida, the results can be applied to areas where similar geological conditions occur. It is noted that carbonate (limestone) units in West Central Florida are relatively recent in age, generally soft and flat bedded. This is in contrast to the Paleozoic Age carbonates in the mid-continent that are flat bedded and very hard or the Appalachian carbonates which are folded and faulted. Geophysical testing approach and data interpretation in these other regions can be very different in comparison to those for West Central Florida.

The specific aspects of geophysical testing that will be discussed are:

1. the importance of selecting appropriate spacing between geophysical transects in order to identify the minimum-sized features of concern,
2. cost considerations based on both data density and desired depth of investigation,
3. value in applying multiple complementary geophysical methods to the same site, and,
4. importance of accurately locating the apparent centers of karst features for future direct testing.

Geophysical studies are being conducted with increasing frequency in karst terrains as part of site characterization studies. The integration of these studies is being driven by both regulatory requirements and an increasing appreciation by the technical community of the advantages of geophysical testing. While beyond the scope of this paper, the authors recognize aerial imagery, geological maps, and site visits are invaluable in karst studies and in designing the geophysical investigations.

2. Geological Setting

Projects cited in this paper were conducted in areas of covered i.e., mantled) karst terrain. In this setting, a sequence of unconsolidated sandy, silty, and clayey sediments overlie limestone. The uppermost sediments are primarily sands with silt and minor clay constituents that are Plio-Pleistocene to recent in age. These sediments range in thickness from 5 to 30 feet (ft) (1.5 to 9.1 meters[m]). The underlying clayey sediments are associated with the Miocene-age Hawthorne Group, range in composition from sandy clays to clay with minor interbeds of limestone and sand and range in thickness from approximately 40 to 65 ft (12.2 to 19.8 m).

The Hawthorne Group sediments are underlain unconformably by the Tampa, Suwannee or Ocala Limestone Formations. Depth to underlying limestone ranges from approximately 12 to 80 ft (3.7 to 24.4 m). When the Hawthorne clays are breached by a collapse of the clay into voids in the underlying limestone, a downward migration of sandy sediments (raveling) occurs. As more and more of the soil column is affected by the raveling, the net effect is that the raveling zone travels upward to the ground surface, ultimately resulting in a cover collapse or cover subsidence sinkhole. In areas where the clayey sediments are not present and the limestone is relatively near the surface, a solution sinkhole may form (For a more complete discussion of the regional geological setting and sinkhole formation, see Tihansky, 1999).

3. Clarification of Terminology

In both geotechnical and geological reports, the term “karst” is often misused and its definition expanded from a descriptive adjective describing a particular geomorphic terrain to implying, in a broad sense, a collection of geological processes and, in a narrow sense, the implication of a sinkhole. A similar misunderstanding occurs with the use of the phrase “paleo-karst” or “paleo-karst activity”.

In simple terms, paleo-karst denotes the presence of an irregular topography in the surface of the limestone formation. This irregular topography is created over geologic time-scale periods by various processes including chemical/mechanical erosion and sinkhole occurrence. Associated with this irregular topography is a significant variation in the thickness and, to a lesser degree, the composition of the overlying sediments. Sinkhole activity is considered to occur when there has been vertical migration of sediments into voids in the underlying limestone. The term “paleo” implies ancient in terms of the geological time scale and does not imply an active process, which is a distinction often missed by both professionals and the general public.

Geophysical anomalies are typically considered present when a significant variation in either lateral or vertical geologic conditions is observed. These variations, however, do not necessarily imply sinkhole activity. These variations can result from depositional or erosional processes. It is not possible by geophysical means alone to determine whether karst features are geologically stable features that formed hundreds of thousands, if not millions of years ago, or whether they are new unstable features with a high potential for future collapse either by induced or natural causes. It is only by use of Standard Penetration Test (SPT) borings or Cone Penetrometer Tests that the nature of an anomaly can be determined. Through this testing it is usually possible to determine if a geophysical anomaly has a high potential for future collapse.

4. Determination of Appropriate Methods for Karst Investigations

From the standpoint of surficial geophysical methods, the detection of karst features is theoretically a relatively easy task. Limestone in an unaltered state is a relatively dense rock with a high seismic velocity and high resistance. Karst features within limestone are alternatively low in density, seismic velocity, and resistance. The sediments overlying the limestone in non-karst areas usually have relatively horizontal and continuous contacts. In karst terrains, these horizons become vertically displaced, distorted and possibly discontinuous. By establishing the probable depth and nature of karst features, the appropriate geophysical methods can be selected. For a study to be successful, it is critical to match the appropriate geophysical method to the physical parameters of the target along with the minimum depth of interest.

The most common geophysical method for karst studies in west-central Florida is ground penetrating radar (GPR) (Zisman, 2006) followed by electrical resistivity imaging (ERI) and various seismic methods including then other seismic methods that include seismic reflection, seismic refraction tomography, multiple channel analysis of surface waves (MASW) and spectral analysis of surface waves (SASW) (Dobecki, 2006)., electromagnetics (EM), and time domain electromagnetics (TDEM). Table 1, below, is a general listing of targets (i.e., karst features), physical characteristics, and recommended American Society for Testing and Materials (ASTM) methods for their resolution (ASTM D-6490-99).

Table 1. Selection of Geophysical Methods for Karst Investigations

Target	Physical Characteristic	Method (footnote)
Vertically Displaced or Discontinuous Soil Horizons	Contrast in Acoustical Impedance Contrast in Electrical Resistivity Contrast in Dielectric Constant	GPR (A,1) ERI (A,1) Seismic Refraction (A,2) Seismic Reflection (B,2) MASW (C,3) EM (B,3) TDEM (B,3)
In-filled (wet) Voids within Limestone	Contrast in Acoustical Impedance Contrast in Electrical Resistivity Contrast in Dielectric Constant Contrast in Density	GPR (A,1) ERI (A,1) Seismic Reflection (B,2) MASW (C,3) EM (B,3) TDEM (B,(3) Gravity (A,3)
Voids within Limestone (dry)	Contrast in Acoustical Impedance Contrast in Electrical Resistivity Contrast in Dielectric Constant Contrast in Density	GPR (A) ERI (A,1) Seismic Reflection (B,2) MASW (C,3) EM (B,3) TDEM (B,3) Gravity (A,3)
Fracture Zones	Contrast in Acoustical Impedance Contrast in Electrical Resistivity Flow of Water	GPR (A,1) ERI (A,1) Seismic Refraction (A,(2) Seismic Reflection (B,2) MASW (C,3) EM (B,3) TDEM (B,3)

A = primary method of choice, ASTM D-6420-99
B = secondary or alternative method, ASTM D-6420-99
C = method has not been considered in ASTM D-6420-99
1, 2, 3 = frequency of use in karst studies conducted in west-central Florida: 1-frequently, 2-less frequently, 3-rarely

To design geophysical surveys for karst studies, five major parameters must be considered:

1. required depth of investigation
2. minimum size of feature to be identified,
3. objectives of the survey (reconnaissance vs. a comprehensive investigation),
4. site accessibility, and
5. budget.

The productivity rates and costs of different geophysical methods are highly variable depending upon the site conditions and survey parameters. A general summary of the cost and productivity factors for the primary geophysical methods used for karst studies in west-central Florida are provided in Table 2, below.

Table 2. General Costs and Productivity Rates for Primary Geophysical Methods Used for Karst Studies in West Central Florida

Geophysical Method	Data Collection Linear Feet/Day (Meters)	Range of Cost/Day[1]	Cost/Linear Foot (Meter) of Data[2,3]	Average Maximum Depth Range in Feet (Meters)[4]
GPR[5]	10,000 - 20,000 ft (3,048 - 6,096 m)	$1,500-2,000	$0.12/ft ($0.39/m)	15-40 ft (5-12 m)
GPR with GPS[6]	20,000 - 40,000 ft (6,096 - 12,192 m)	$1,800-2,300	$0.07/ft ($0.23/m)	15-40 ft (5- 12 m)
ERI[7]	2,000- 3,000 ft (610 - 914 m)	$1,800-2,300	$0.82/ft ($2.69/m)	150-250 ft (46-76 m)
Seismic Reflection[8]	1,200 - 1,800 ft (365 - 549 m)	$2,500-3,500	$2.00/ft ($6.56/m)	100-300 ft (30-91 m)
MASW[9]	1,000 - 2,000 ft (328 - 656 m)	$2,500-3,500	$2.00/ft ($6.56/m)	50-80 ft (15-24 m)

1. Costs are average for projects performed by author's firm for local projects in 2007 and are not meant represent price ranges for other service providers
2. Calculated using mid-range of footage and cost parameters
3. Costs per linear ft are for full or multiple day projects and cannot be used for smaller partial-day studies
4. Depths of investigation for GPR are primarily controlled by soil conditions and depth to ground water, for ERI are primarily controlled by transect length, for seismic reflection the size of the site and selected energy source, and for MASW by limitations of the method and size of site.
5. Assuming GPR data are collected across an established grid using hand pushed cart or pulled antenna
6. Assuming GPR data are collected using an integrated GPS system and towed behind a vehicle
7. Assuming a 10-ft electrode spacing
8. Assuming a 10-ft spacing between geophones
9. Assuming a 3-ft spacing between geophones with geophones mounted on land streamer

As shown in the table, GPR is the most cost-effective method on a per linear foot basis and also provides information with the highest resolution. However, GPR is the most limited in terms of the depth investigated. Comparatively, MASW or seismic reflection are roughly 20 to 30 times more expensive on a per linear foot basis. However, seismic reflection will provide information to depths of several hundred feet and MASW will provide shear wave velocities. Depending upon the needs of a particular project, the relative differences in costs could be irrelevant. Alternatively, if the objective of a project is to identify karst features within a depth range of 20 to 30 ft (6 to 9 m), GPR, under favorable conditions, would provide a much more complete survey of a project site for a given budget than, for example, ERI.

5. Selection of Appropriate Transect Spacing

The selection of the appropriate spacing between geophysical transects for a particular method is controlled primarily by the minimum target size one can detect with the available budget, or, alternatively, what size of a feature the client is willing to miss for the available budget. In West Central Florida, the average diameter of sinkholes (at land surface) is 11.2 ft (3.4 m) with a median value of 6 ft (1.8 m) (Zisman, 2006). Using the methodology provided by Benson (1984), in a 1,120 ft^2 (104 m^2) area 10 borings would be required to find a 11.2 -ft (3.4 m) diameter sinkhole with a 90 percent (%) confidence level. For an area of 50,000 square ft (4,645 m^2), 446 borings would be required to obtain a 90% confidence level. Such a large boring program would typically be cost prohibitive, while using geophysical methods that confidence level can be obtained with a small budget.

While the relationship between probability of detection and frequency of boreholes is a simple mathematical relationship, the relationship between the probability of detection and frequency of spacing between geophysical transects is not as clear. This is because of the influence caused by subsurface "off-line" features. This off-line sensitivity occurs because the response of the various geophysical methods is a product of a bulk volume of earth materials rather than a discrete point. For example, the electrical resistivity imaging

(ERI) method evaluates the resistivity of soil materials within an ellipsoidal area formed between the outermost electrodes. For the GPR method, the wave front emitted from the GPR antenna emanates laterally approximately 30 degrees from vertical. Further complicating the GPR response is the fact that the offline reflecting surface must have some portion of its surface perpendicular to the wave front of the incoming wave. It is the authors' experience when using electrical or seismic method, that a transect spacing equal to 1.3 to 1.5 times the minimum diameter of interest *for* the karst feature is usually sufficient to identify the majority of such features. For GPR a transect spacing equal to 1.5 to 2.5 times the minimum diameter of interest, the target diameter is usually sufficient. This is primarily because GPR surveys are usually conducted in two directions, while the other methods are conducted in only one direction.

For small sites of 1 to 2 acres (4,406-8,094 m^2), deciding on the accepted probability of missing a feature is usually not a concern since these studies can be conducted (assuming that GPR is used) for the cost of a one-day survey. However, for larger sites of 5 to greater than (>) 10 acres (20,000 to >40,000 m^2) the cost for a detailed survey can be significant relevant to the overall geotechnical budget. A good compromise for these projects is to provide a detailed survey within and just beyond the boundaries of the building footprint or in other areas of critical concern such as retention ponds. A more coarsely spaced survey (i.e., less detail), can be conducted in less critical areas, such as the parking lot or open space, where more risk is acceptable.

For a large site where the actual locations for critical structures (e.g. a landfill cell) are not known, a detailed survey is usually not warranted or financially feasible. In these situations, a reconnaissance-style survey can be performed where a representative overview of site conditions is sufficient. Figure 1, below, shows the location of GPR transects results for a GPR survey conducted over a 130-acre (526,100 m^2) landfill study site. The survey was performed using a series of perpendicular transects spaced, where feasible, approximately 100 ft (30 m) apart.

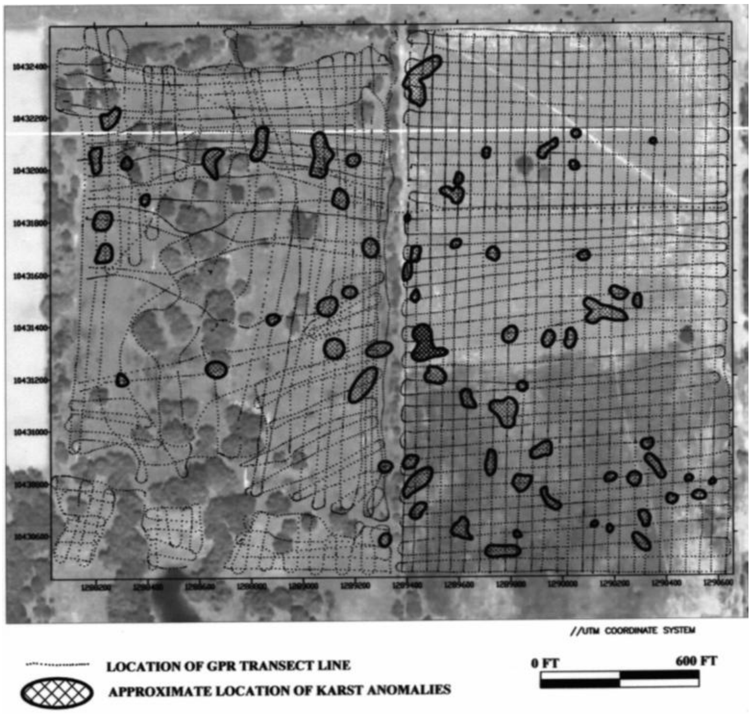

Figure 1. Results of reconnaissance-style GPR survey on 120 acre (48.6 hectares) area using a vehicle-towed GPR system with an integrated GPS system

At large sites, data are acquired by towing the GPR antenna behind an all-terrain vehicle and data positioning is provided using sub-meter accuracy, integrated global positioning system (GPS). In the case of the landfill study, GPR results were used to determine which portions of the site were not suitable for the siting of 20 to 30 acre (80,937 to 121,405 m^2) landfill. Based on the survey results it was determined that the northeast quadrant of the property is most favorable (from a karst standpoint) for the placement of a landfill. A more detailed geophysical survey involving multiple methods is planned when the actual location for the landfill cell is determined.

In the landfill study, approximately 160,000 linear ft or 30 miles (48.5 km) of GPR data were obtained in a five-day period for a total project cost of under $13,000. Using GPR methods, it was possible to characterize the site to determine the most favorable areas for locating the landfill at a cost of approximately $100 per acre (0.4 hectares).

6. Cost vs. Depth

Besides the size of the project area and desired level of detail, the required depth of investigation will have the greatest impact on the project cost and required time for completion. In most instances, increasing the required depth of investigation will increase the cost per linear foot of data.

For example, consider a two-acre site (refer to Table 2) where a detailed GPR study using a grid system of transects spaced 10 ft (3 m) apart can most likely be conducted for less than $2,000. An ERI study with parallel transects spaced 20 ft (6 m) apart would be two to three times more expensive than the GPR study while a seismic reflection or MASW study could cost four to five times as much. Each of these alternative technologies would provide less detail (and data) than the GPR study but the other methods would provide data at a greater depth and would provide data in conditions not suitable for GPR studies.

To illustrate, let us assume a hypothetical site with the following conditions: a surficial sand stratum ranging in thickness from 10 to 20 ft (3-6 m) underlain by a clay stratum followed by limestone extending from a depth of 40 to 60 ft (6-18 m) below land surface (bls). GPR will most likely be able to image the interface between the surficial sand and underlying clay stratum and depending upon the saturation state and composition of the clay, GPR may be able to image 3 to 7 ft (1-2.1 m) below the sand/clay interface for a total depth of investigation ranging from 13 to 27 ft (4-8 m) bls. If the objective of the survey is to help establish the cause of damage to an existing structure or help provide assurance that the ground can support a shallow foundation for a relatively light structure, then the depth information obtained by the GPR is most likely adequate.

However, if the geophysical investigation was being conducted as part of a geotechnical investigation for a high-rise building or elevated roadway/overpass, then a GPR-only investigation would not be adequate because stress from these structures would be carried to depths beyond the reach of GPR methods. An example is provided for a project where the pier for an aboveground structure had settled nearly 12 ft (4 m). The bottom of the shaft was approximately 72 ft (22 m) with depth to limestone rock at 65 ft (20 m) bls. It is noted that no geophysical testing was done prior to the construction of this structure and results from the SPT boring for the shaft did not indicate an elevated risk for karst activity.

Very soon after the collapse, a geophysical investigation was initiated to establish whether the cause of the collapse was construction or geology related. GPR provided results to a depth of approximately 20 ft (6 m) bls where no disturbance to the near-surface soils was observed. A high resolution seismic reflection survey was then conducted on either side of the collapsed pier. Results from this study indicated the pier in question was located within a large diameter paleo-collapse (i.e., sinkhole) feature (Figure 2). Subsequent deeper SPT borings indicated the presence of extremely weak earth materials consisting of marls and weathered limestone beginning at depths 5 to 10 ft (1.5 to 3 m) below the initial boring. It was also determined that the depth to limestone varied from 10 to 15 ft (3 to 4.5 m) over distances of less than 20 ft (6 m) in the area of the pier.

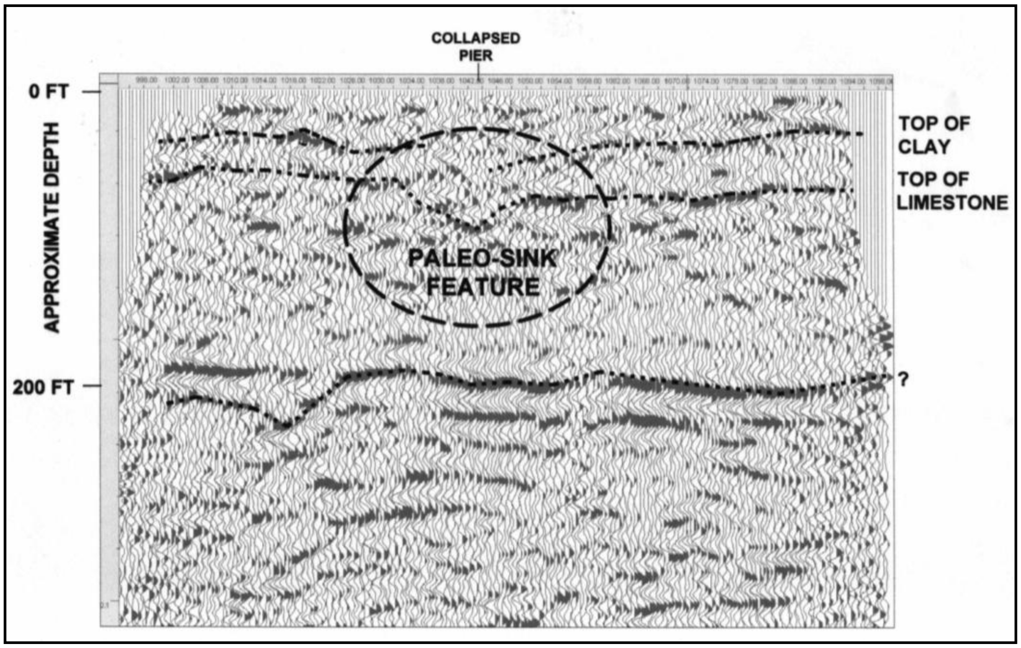

Figure 2. High Resolution Seismic Reflection Cross-Section Showing Paleo-Sink Feature under Collapsed Pier. Note: sediments within the depth range of the GPR signal. i.e., 15 to 20 ft (4.5 to 6 m) bls, were not affected.

7. Multiple Methods

The use of appropriately selected multiple geophysical methods usually enhances the quality and value of geophysical studies. The typical combination is GPR, which provides a very high resolution of near-surface conditions, coupled with ERI or a seismic method that will provide information to a greater depth but with a reduced resolution.

An example of appropriately selected multiple geophysical methods is provided by a project site near downtown Tampa, Florida. Near-surface stratigraphy consisted of a surficial sand 8 to 12 ft (2.4 to 3.7 m) in thickness underlain by a variable clay stratum with interbedded limestone ranging in depth from 10 to 15 (3 to 4.5 m) ft bls. The limestone interbed was 5 to 10 ft (1.5 to 3 m) thick and was underlain by sand underlain in turn by competent limestone at a depth of 25 to 30 ft (8 to 9 m) bls. Initial geotechnical testing indicated the upper limestone stratum was heavily weathered with loose to very loose overlying soils. Analysis of results from the initial geotechnical investigation called into question whether the planned shallow foundations would provide adequate support for the proposed complex of three-story buildings.

A geophysical investigation was conducted to establish the lateral extent of near-surface karst activity and help determine whether shallow foundations with shallow grouting or deep foundations would be appropriate. A GPR study was conducted on a 10-foot (3-meter) grid across each of the planned building footprings. ERI transects were conducted across all GPR anomaly areas and in any areas where karst activity was identified by the SPT borings (Figure 3).

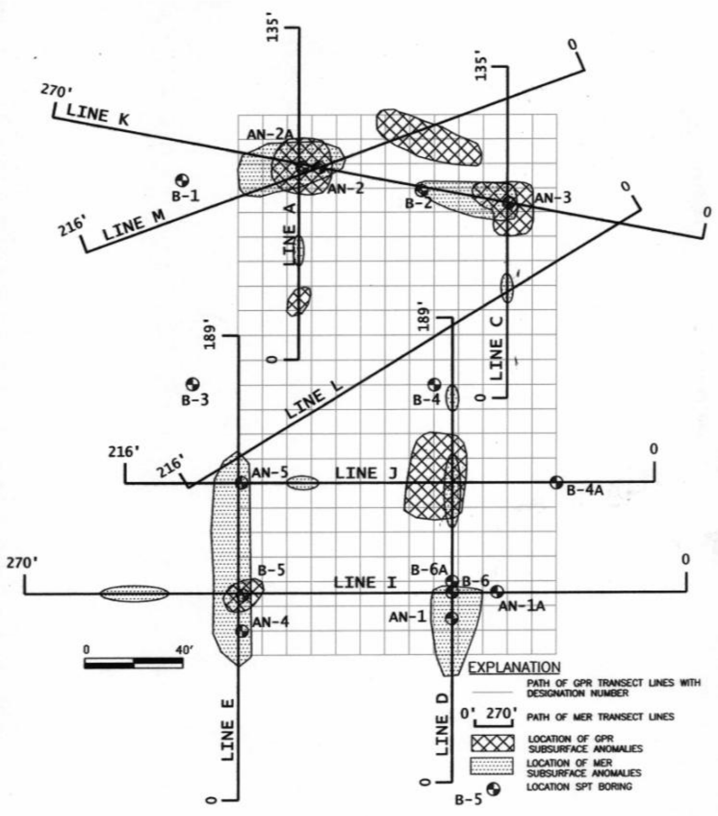

Figure 3.Site Plan Showing Location of GPR and ERI Anomalies

The multiple geophysical methods study showed the GPR was able to effectively image the top of the clay stratum but was not able to image the top of the upper limestone stratum whereas the ERI data were able to image all layers including the lower limestone stratum. Upon completion of the geophysical survey, an extensive geotechnical testing program was completed to confirm the geophysical results. Based on comparison of the geophysical and geotechnical studies, the following was concluded:

- Each GPR anomaly had a corresponding ERI anomaly.
- The SPT borings showed karst conditions were encountered in each GPR/ERI anomaly area.
- Several ERI anomaly areas were identified that did not have corresponding GPR anomalies. However, several of these anomalies were false positives.
- The ERI method overestimated the diameters of the karst features while the GPR method accurately estimated the diameters of the features.
- The ERI results indicated karst activity was limited to the stratum above the lower limestone, which was subsequently confirmed by the geotechnical borings.
- The GPR method was more accurate in determining the location of the centers (i.e., throats) of the karst features for follow-up geotechnical testing (see following discussion Section 8, Targeting Test Locations).

The geophysical and follow-up geotechnical investigations established that near-surface karst conditions were present primarily, based on the GPR results, and karst conditions were limited to the unconsolidated materials above a depth of 20 to 30 ft (6-9 m) bls, based on the ERI and geotechnical results. Using these results, it was decided that deep foundations would provide the most economical method of foundation support. It is important to note that without the use of geophysical testing, the interaction of karst in the subsurface may have resulted in selection of a foundation susceptible to movement.

8. Targeting of Test Locations

A primary purpose in geophysical investigations is to provide optimal locations for test borings in order to provide a representative characterization of site conditions. When project objectives and soil conditions allow, GPR provides superior information compared to other methods. The reasons for GPR's superiority include:

- The GPR data have the highest resolution. GPR data points are typically collected at an interval ranging from 0.08 to 0.15 ft (2.4 to 4.57 centimeters [cm]). This provides in effect a continuous profiling along a transect. In terms of resolving a particular feature, GPR typically loses 0.5 to 1 inch (1.27 to 2.54 cm) of resolution capability per foot of burial with resolution decreasing with lower antenna frequencies. In comparison, seismic and ERI studies are typically collected with data points 3 to 10 ft (1 to 3 m) apart with the theoretical maximum resolution being one-half the electrode or geophone spacing. This maximum resolution decreases with depth.
- Because of the lower cost per linear foot, much more data are typically collected in GPR investigations than with the other methods.
- The GPR data are typically collected in two directions rather than just one as in the other methods. This is relevant because karst features are often asymmetrical and the most definitive response from any geophysical method is typically perpendicular to the long axis of the feature.
- The GPR data can easily be evaluated in real time, during data collection, which allows for additional transects to be adjusted as needed to help establish the center of the feature. Data from other methods are typically analyzed in the office and budgets are rarely available for "go backs" to further define identified anomalous features.

An additional consideration is that ERI and seismic results are affected more than GPR by features which occur off or away from the transect line. This is an inherent problem when trying to represent three-dimensional geological conditions with a two-dimensional transect. This is often a difficult concept to relate to clients where the perception is that the seismic or ERI results provide a knife-edge vertical cross-section view through the subsurface and all identified features are directly below the transect line.

9. Sample Case Study of a Cost Savings Associated with a Geophysical Investigation

The site was a two-acre parcel in Tarpon Springs, Florida, where a 20,000 ft^2 (1,858 m^2) commercial building was planned. The site is located in an area of known karst conditions. The site layout and building design were performed prior to the geotechnical site investigation and without the benefit of a geophysical investigation. Results from two of the three SPT borings drilled at the site indicated the presence of karst conditions. Based on this information, the owner was given the alternative of paying more than $100,000 for a compaction grouting program or continuing the geotechnical investigation to find a more suitable portion of the site where such improvements would not be required.

The option of finding a more suitable area on the site for the construction was selected and a geophysical investigation was initiated. Results from an initial GPR survey established that the GPR signal could not penetrate to the depth of known karst activity. Accordingly, an ERI survey was conducted using a series of parallel ERI transects spaced 20 ft (6 m) apart across the property. Results of the ERI survey confirmed the presence and lateral dimensions of the karst features identified by the initial SPT borings and an additional area of previously unknown karst conditions. The survey also delineated an area that appeared to be an appropriate placement for the building using a conventional shallow foundation. Results of the ERI investigation were confirmed with three additional borings. Based on the geotechnical borings and the geophysical data, the location of the building was shifted to the unaffected portion of the site where shallow foundations could be used, thereby saving the client the cost of compaction grouting or deep foundations.

This construction project was delayed about two months due to the required additional testing and engineering. Had the geophysical investigation been performed prior to the geotechnical and civil engineering aspects of the project, the following direct and indirect costs would not have been incurred:

- Cost of three additional SPT borings: $3,500
- Cost of additional geotechnical-related reports and staff time: $2,000
- Cost of re-engineering the project: $2,500
- Cost of a two-month construction delay

The geophysical investigation was conducted for less than $4,500. If the geophysical investigation had been performed first, a direct cost savings of $3,500 would have resulted and without a delay in the project. While the associated direct cost savings of $3,500 is relatively minor, the savings associated with the avoidance of compaction grouting program were substantial.

10. Summary and Conclusions

The information obtained by a properly designed geophysical study in karst conditions can significantly improve the accuracy and completeness of geotechnical investigations. When deciding which method to use, one should consider the following:

- Most conditions that typify karst activity can be identified by one or more geophysical methods and the applicability of a particular method is dependent upon site specific conditions.
- Productivity rates and cost per linear foot of geophysical data vary greatly. GPR is the most cost effective but sometimes the most limited of the methods.
- Selection of transect spacing is controlled by the objectives of a survey. The question that must be asked in the planning process is: What size feature are you I willing to missed as a result of survey design?
- The selection of a particular method must take into account the required depth to which karst conditions are of a concern.
- Generally, as the depth of the investigation increases, the cost per linear ft will increase.
- Appropriately selected multiple methods will usually provide superior results in comparison to use of a single method.
- It is important to provide the optimal testing location for a karst feature. GPR typically provides the most accurate information. Other methods such as seismics and ERI are more susceptible to the effects caused by off-line subsurface features.
- By first performing geophysical investigations, engineering costs for a project can be reduced and expensive soil stabilization efforts can be avoided or minimized.

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