GEOTECHNICAL/GEOPHYSICAL EVALUATION OF KARST LIMESTONE SITES – A CASE HISTORY

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Abstract

A collaborative effort between a geotechnical engineer and geophysicist in conducting subsurface evaluations of a karst limestone site is demonstrated with this case history. The example shown here from southwest Missouri, demonstrates how the traditional geotechnical approach to investigating karst limestone sites can be adapted to embrace the use of geophysics. The site was found to contain active sinkholes, which were of potential concern to the engineer. Terrain conductivity, 2-dimensional resistivity imaging, drilling and downhole logging were combined effectively on this fast-moving and resource-limited project on a large acreage site. In the case history presented, the geophysical results were used as a guide by the geotechnical engineer as he made decisions about recommendations for foundation design. The end result was the geophysical information gave the geotechnical engineer and his client what they wanted - greater assurance that they had exercised diligence in their efforts to define site conditions and avoid hazards.

Introduction

There are a number of geophysical methods that have been tested and applied to the investigation of karst limestone sites, albeit with varying degrees of effectiveness in achieving project objectives. To name a few, P-wave and S-wave refraction/reflection seismic, spectral analysis of surface waves (SASW), gravity, ground penetrating radar, 2D and 3D resistivity imaging, and electromagnetic conductivity have all been tested and evaluated with mixed results. In practice, the choices of methods available to a geophysical consultant are often dictated by factors pertinent to clients such as cost, speed, method reliability, anomaly resolution, and data interpretability. Confidence that the geophysical survey will do a reasonable job in portraying site conditions is critical to the client, the consultant and their professional relationship.

Ideally, geophysical surveys should be conducted in a manner that guides the scope of the drilling portion of the engineer's subsurface investigation. However, in reality, the geotechnical engineer will often seek the assistance of the geophysicist after an initial round of drilling has been completed, and after the potential risks associated with karst are realized. Sometimes this realization can even come as late as the construction or post-construction phase when it is too late. The geotechnical engineer is confronted with the ineffectiveness of the "hunt and peck" drilling method for mapping karst features, especially at large sites. He/she approaches the geophysicist with a desire for increased confidence and reassurance that a reasonable effort has been made to define karst features. As such, the geophysical methods chosen would be expected to provide a good indication of the depth to bedrock or at least the shape of the bedrock surface, variations in soil characteristics potentially effecting engineering design, fracture (pinnacle and grike) orientations, as well as the more critical features such as caves, voids, soil pipes, and sinkholes.

The rationale for geophysical method selection is certain to evoke debate among geophysical professionals, as it is both a reflection of the consultant's education and experience, preferences and motivations and the client’s budget, schedule, and knowledge of, experience with, and/or opinions about, geophysics. Judging by the number of relevant papers and presentations over the last four or five years, it has become increasingly evident that the application of resistivity imaging, often combined with other methods, to karst problems has gained wider acceptance. For example, Roth et al. (1999) addressed the application of 2-dimensional resistivity in thinly mantled karst at a scale appropriate to foundation design applications. Their application of 2-dimensional resistivity imaging as a guide to the selection of soil boring locations for a geotechnical investigation proved valuable, although a number of limitations were noted. Because of the complex 3-dimensional nature of the site studied, it was evident that the 2-dimensional resistivity results often reflected the features outside the plane of cross-section. The obvious appeal for the application of 2-dimensional resistivity imagining is in its ability to provide a visually meaningful result to a non-geophysical client that is a fair representation of subsurface conditions. Roth et al. (1999) points out that the advent of multi-electrode earth resistivity systems and the availability of 2-dimensional resistivity inversion modeling software have made the routine application of resistivity imaging feasible.

Zhou et al. (1999) conducted an extensive, gridded 2-dimensional resistivity imaging project consisting of 49 transects in a 10-acre area at a karst limestone site in southern Indiana. Their method of determining the elevation of the top of bedrock yielded an average difference relative to borehole data of about 0.4 meters, an excellent result. Despite this positive outcome, however, one clear downside to the approach used by Zhou et al. (1999) is the level of effort required to achieve the project objective. At an assumed rate of about seven transects per day, coverage of a 10-acre site would require about one week of field time. In addition, inversion and interpretation of a large number of transects would clearly require a significant amount of time as well, perhaps several weeks. We speculate that the time and cost for this level of effort might receive significant resistance from the client. The approach we present in this paper attempts to make the speed and cost of karst investigation more desirable without significantly compromising the degree of coverage of the subsurface.

Technical Approach

Our client, a geotechnical engineer, through his prior investigative efforts, had already determined there was a need for a geophysical survey. His investigations had established that sinkholes were present at the site and that an undulating bedrock surface was present, indicative of karst activity. The technical approach used on the case history presented here is similar to the multi-step approach taken by others such as Ahmed and Carpenter (2001). It begins with reconnaissance mapping with terrain conductivity to form a basic understanding of the soil and bedrock relationships in terms of apparent conductivity or resistivity, preferably at a few depth levels. The interpretive emphasis is directed towards potential air or fluid filled voids and solution-enhanced features, such as grikes, which could contain underconsolidated soils (i.e., materials with high moisture content and low shear strength). Interpretation of the terrain conductivity data is augmented with 2-dimensional resistivity imaging within the context of the interpreted terrain conductivity data. The next step is direct calibration of the geophysical data. Drilling and sampling at key anomalies, combined with downhole geophysical logging in the open borings, provides a link between the geologic observations and the surface geophysical data. Finally, the terrain conductivity and 2-dimensional resistivity data are reprocessed and reinterpreted and a final geologic model is developed. This approach, applied to the subject site, and other sites, has proven to be a useful tool in the investigation of karst limestone sites. It has been shown to be relatively rapid and cost effective while still providing a reasonable degree of assurance to the geotechnical engineer that significant karst features have been addressed.

Background

Site Description

The project site is located near the town of Republic, Missouri, a few minutes southwest of Springfield (Figure 1). At the time of the geophysical investigation in 2000, the site was about 25 acres of overgrown, undeveloped land, which was undergoing initial site design for a future retail store. There is about 30 feet of relief across the site, and a valley sloping from the northwest to the southeast bisects the site. The valley is at the head of a losing stream, and a well-defined sinkhole in the southeast corner of the site receives the surface run-off from the entire site.

Prior investigations at the site by the geotechnical engineer had included over 60 soil borings. Their findings indicated that the depth to bedrock was highly variable, ranging from the surface to over 20 feet (or more) in depth. Concerns by the geotechnical engineer pertained to both the highly irregular bedrock surface and the known existence of sinkholes. There was also concern about the possible existence of additional undiscovered sinkholes or incipient sinkholes just beginning to undergo formation. The geotechnical engineer recommended to his client that a geophysical investigation be conducted to locate karst features before he would recommend site development.

Figure 1. Site location map. Republic is located about eight miles southwest of Springfield, Missouri.

Site Geology

Republic, Missouri is located in the Western Plains physiographic region, and the site is underlain by Mississippian age Burlington-Keokuk Limestone. The limestone is a light gray, coarsely crystalline, fossiliferous unit, highly susceptible to solution. A prominent feature of the bedrock is the formation of pinnacles and grikes, represented by prominent knobs (pinnacles) of bedrock bounded by deep troughs (grikes) caused by dissolution in fractures. The limestone bedrock was subjected to structural forces from the Ouchita Orogeny and has undergone some structural deformation. The geologic structures resulting from this deformation appear to have controlled the development of karst. Fractures in the region are oriented northwest and northeast.

Karst features are prevalent throughout the study area. The sinkholes occur when carbonic acid (H_2CO_3) from atmospheric carbon dioxide and rainwater percolates downward into subsurface waters and dissolve carbonate bedrock. This process continues enlarging fractures into cavities that may collapse, causing a sinkhole. In the study area, a sinkhole is positioned in a structurally low area, with all surface water draining into the sinkhole. This sinkhole lies above a northwest-southeast lineament feature (regional in scale) that cuts across the central portion of the site. The losing stream at the site is at the head of valley that has numerous sinkholes found along its entire 1.5 mile length.

The site is approximately 50 feet in elevation above the nearest perennial stream, located about 1.5 miles to the south. Observations during the drilling of soil borings at the site indicated that groundwater is not present down to at least 45 feet below the lowest location drilled. Thus, it appears that groundwater is found relatively deep at this site. Since the limestone bedrock is in an unsaturated condition in the volume investigated, it is likely there is a significant resistivity contrast between the dry limestone and the moist, clay-rich residual soils.

Initial Field Investigation

Terrain Conductivity Reconnaissance Mapping

The approximate site dimensions were 1300 feet by 1300 feet. Because much of the site was covered with heavy undergrowth and piles of debris (due to past dumping), it was necessary to clear walking paths for the field personnel to collect terrain conductivity data. Parallel north-south lines spaced 50 feet apart were selected. After the ground preparation work was completed, terrain conductivity data were collected with a Geonics EM-34 Terrain Conductivity Meter along each of 26 lines. The in-line data point spacing was 25 feet. Data were collected with the 10-meter coil separation in both the horizontal and vertical dipole modes. The two coil orientations allowed sampling at two depth levels. The vertical dipole will “see” about twice as deep as the horizontal dipole. The EM-34 has a variable coil separation of 10, 20, or 40 meters. Under ideal conditions these give maximum depths of penetration of 15, 30, and 60 meters respectively for the vertical dipole orientation. The maximum response for the vertical dipole mode is at a depth of about half the coil spacing, or about 5 meters (about 16 feet) in this case. The maximum response for the horizontal dipole mode is at the surface. Decisions regarding coil separation and data point spacing were derived from prior knowledge of the site provided by the client. Generally, prior drilling had indicated the soil mantle is relatively thin beneath the most critical portions of the site.

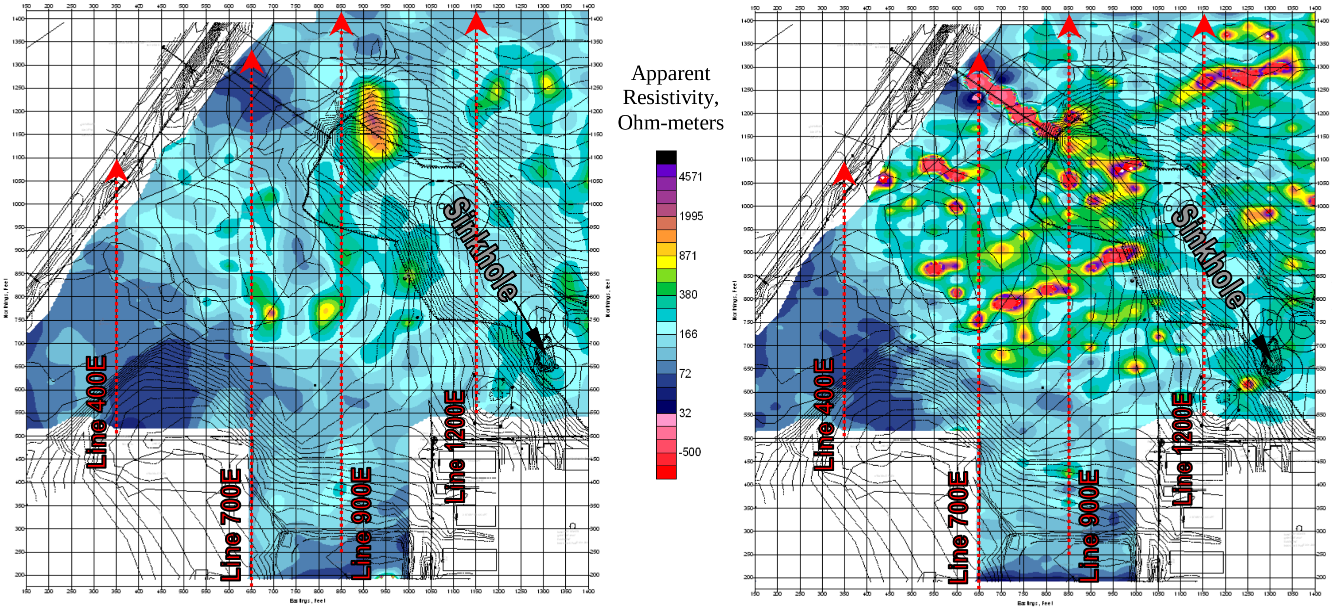


Figure 2, EM-34 Horizontal Dipole Map (left) and Figure 3, EM-34 Vertical Dipole Map (right). The coils were separated by 10 meters. Data are presented in ohm-meters resistivity with a lognormal color scale. High resistivity values, green to yellow to purple, are interpreted as being dominated by bedrock. Conversely, soil-dominated areas correspond to light to dark blue color. Negative values (red) on the vertical dipole correspond to two specific things. At the head of the valley is a northwest trending negative that was caused by a steel drainpipe. Negative values are also found at the crests of the high resistivity ridges interpreted as pinnacles at the highest values; these negative values correspond to extremely resistive limestone bedrock. Topographic contours (black) are superimposed over the maps. The northwest trending valley on the eastern side of the site leads to a known sinkhole area to the southeast. Surface water flows into the sinkhole in the center of the valley. The four red dashed lines are the locations of the 2-dimensional resistivity profiles (Figure 4).

The data stored in the data logger were in the form of apparent conductivity in milliSeimens per meter (mS/m). These values were converted to apparent resistivity for mapping purposes. This was accomplished by inverting the apparent conductivity data and multiplying by 1000. The resulting apparent resistivity data were in units of ohm-meters. The final processed EM-34 data are plotted on Figures 2 and 3, which are the horizontal dipole and vertical dipole maps, respectively.

2-Dimensional Resistivity Imaging

The locations where 2-dimensional resistivity imaging could be performed were restricted to the pathways cleared for the EM-34 mapping. Due to the heavy undergrowth and debris between the pathways, only north-south resistivity profiles could be acquired. Resistivity data were acquired with an Advanced Geosciences, Inc. Sting R1 resistivity meter and a Swift automated electrode system equipped with 30 electrodes. The electrode separation was 20 feet. Four locations believed to be representative of the Site were selected for presentation (400E, 700E, 900E, and 1200E). The locations of these four lines are shown in red on Figures 2 and 3.

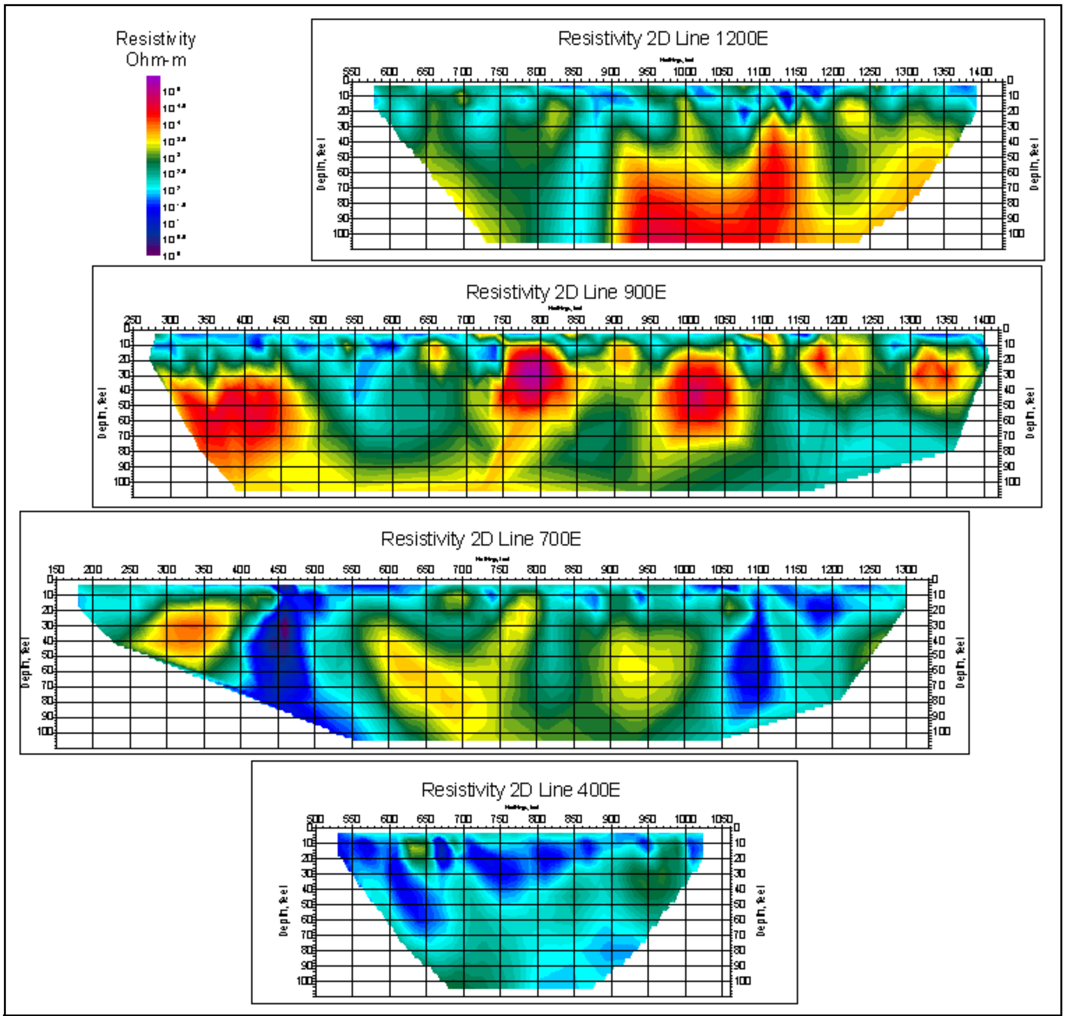


Figure 4. The four 2-dimensional resistivity profiles. The dipole-dipole array data were modeled using RES2DINV. The color scale used is lognormal ranging from dark blue for low resistivity through red and purple for very high resistivity. The low resistivity areas, dark blue to cyan, were interpreted as mainly soils. High resistivity, yellow to red to purple, was interpreted as limestone bedrock. It is also possible that air filled voids could be present, and they too would have high resistivity. The extreme range of resistivity values (5 orders of magnitude) suggests that significant overshoot in the modeling has occurred. Later downhole logging would indicate there are about two orders of magnitude of resistivity variation (about 10^1 to 10^3 ohm-meters).

The 2-dimensional resistivity data were acquired in the dipole-dipole array mode for all four cross sections. The apparent resistivity data were modeled using RES2DINV. The results of the 2-dimensional resistivity modeling for the four lines were plotted as 1:1 resistivity cross sections presented in Figure 4. Line 1200E was later remodeled (Figure 7) after additional field investigation was concluded. The downhole logging would later show that the range of resistivity variation at the extreme was about two orders of magnitude (10^1 to 10^3 ohm-meters).

Discussion of Initial Field Investigation Results

The horizontal dipole map (Figure 2) shows the apparent resistivity (essentially the volume-weighted average) down to a maximum depth of about 7.5 meters. The horizontal dipole mode emphasizes nearer surface features in its measurements. Therefore, this map is a reflection of the shallower subsurface materials (generally residual soils, fill, or weathered bedrock). It has been assumed that apparent resistivity on the horizontal dipole map reflects primarily variations in the depth to bedrock, but also variations in soil porosity, moisture content, and clay content. Large accumulations of cherty soil found at various locations around the site may also display high resistivity. Lowest resistivity values (darkest blue, less than 100 ohm-meters) are interpreted as thick soil layers, which may also be higher in moisture content. Conversely, shallow bedrock, especially more competent rock, has higher resistivity anywhere from light blue on up to green (low to mid 100's ohm-meters), yellow or orange in color (high 100's to low 1000's ohm-meters) for the shallow and/or most compact bedrock. The apparent resistivity data on Figure 2, since essentially volume weighted toward the near subsurface, correspond to the depth to bedrock in areas where bedrock is relatively shallow (or where soil is resistive, i.e., cherty). Note that the horizontal dipole data on Figure 2 show a number of isolated high resistivity areas, especially in the center and east parts of the site. Comparison with drilling generally confirms that this map is a reflection of depth to rock in these areas. However, it should be noted that in some of the geotechnical borings it was reported that very shallow rock was encountered in areas where the resistivity does not suggest shallow rock. In some of these cases it is likely that a boulder, ledge or cherty soil was encountered, features which would probably not be revealed by the resistivity mapping.

The vertical dipole resistivity map (Figure 3) is a deeper apparent resistivity map. This map reveals apparent resistivity down to about 15 meters below grade, but unlike the horizontal dipole, the signal is focused more towards the center of the measurement volume, or about 7.5 meters. Thus, higher resistivity values would be expected over a greater portion of the map where competent rock was present at depth. In the central and eastern portions of the site, northeast and northwest alignments are very apparent, and together they form a "waffle" pattern. We interpret this as a regular pattern of pinnacles and grikes along the top of the bedrock; these probably follow fractures or joints. This pattern is interrupted by the valley in the center of the site; the valley appears to follow a deep structure, the southeast end of which is found an active sinkhole with drains.

A note is made about interpreting the vertical dipole data on Figure 3. There are a number of negative resistivity anomalies on the map. One such anomaly coincides with an 18-inch metal pipe on the northwest corner of the site. Metal objects, especially linear objects such as metal pipes, will create a negative anomaly flanked by very low positive resistivity readings. However, there also are negative anomalies at the site that do not have this typical metal character. These anomalies, generally oriented east-northeast, are at the core of very high positive resistivity anomalies; these anomalies are an artifact of the process of converting from conductivity to resistivity. The bedrock in these areas is very resistive, and the EM-34 is very insensitive in such environments. The EM-34 can be slightly out of calibration in very resistive environments and yield negative conductivity values.

In the southern and western portions of the site, the apparent resistivity is found to be relatively low (light to dark blue, less than 100 ohm-meters) on both EM-34 maps. It appears these areas are dominated by soils or fills and little bedrock is apparent. The deepest blue shading suggests that these soils are relatively moist, clayey soils.

The four resistivity cross sections (Figure 4) are modeled from apparent resistivity data collected in the dipole-dipole array mode. The model solutions are only an approximate representation of the subsurface as they are a 2-dimensional representations of complex 3-dimensional structures. Since electrical current will follow the path of least resistance, distortions may be created by low resistivity features outside the plane of data collection. Additionally, the resolution of this method decreases with depth in an exponential fashion. The highest resistivity reflects the presence of competent rock that is low in moisture and relatively massive (yellow to red, 1000's ohm-meters). Weathered, fractured bedrock is more likely to be dark green to yellow (100's to 1000's ohm-meters). Residual soil will vary from deep blue, light blue, light green, to dark green (10's to 100's ohm-meters) depending on moisture content. Air filled voids may appear as high resistivity levels as well.

In general, the shape of the bedrock surface appears to be very irregular along Lines 700E, 900E, and 1200E. Several locations indicate weathering may have extended very deep into rock (See for example Line 700E at stations 800-850N, Line 900E stations 500-700N, and Line 1200E stations 800-900N). A number of other examples of this complex weathering pattern exist across the site.

Weathering appears to go deep in the sinkhole area on the southeastern corner of the Site as was expected (see Line 1200E, station 580 to 900N). Within this zone overhangs and pinnacles are possibly indicated. Again on Line 1200E, a deeply weathered zone is apparent from 1200N to 1250N. Lines 700E and 900E have several areas where potential karst features are indicated at depth.

Additional Field Investigation

The intent of the additional field investigation was to determine the causes of electrical resistivity anomalies believed to indicate possible karst features revealed during the initial investigation discussed above. The goal was then to develop a refined interpretation of the geologic setting of the site. The area of additional investigation was restricted primarily to the extent of the proposed building location on the east side of the site, although reinterpretation of the entire original study has been conducted. The scope of the fieldwork for this investigation consisted of drilling into the bedrock at eight (8) key locations across the area of investigation and conducting borehole geophysical logging to supplement the surface geophysical data. These eight boring locations are shown on Figure 5.

Figure 5 also contains the EM-34 vertical dipole map from Figure 3. Along

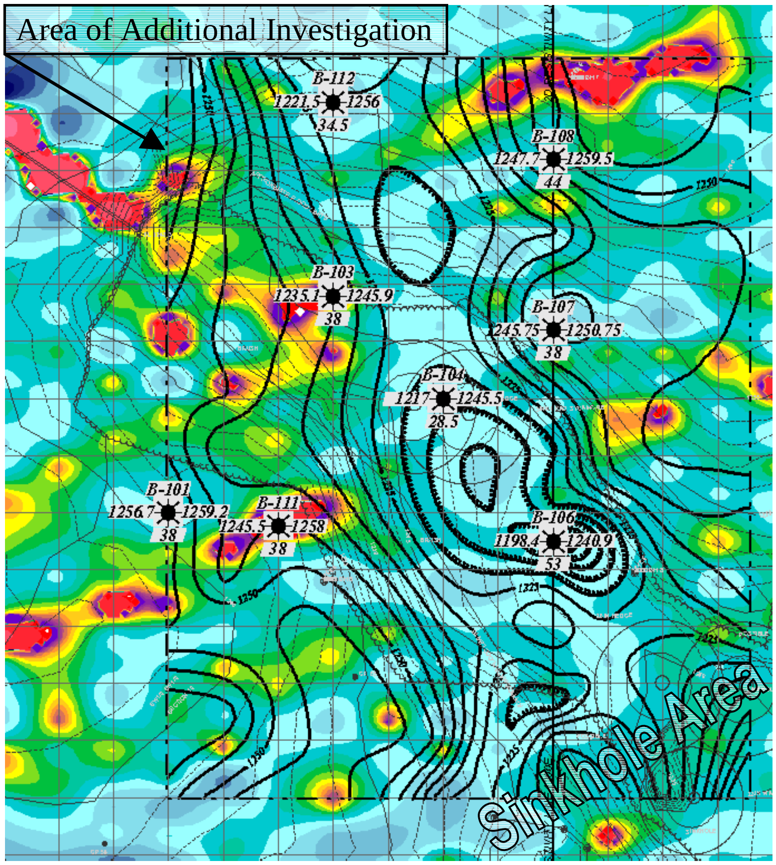


Figure 5. Portion of the EM-34 vertical dipole map showing area of additional investigation. The contour map overlay (heavy contours) depicts the interpreted elevation of the top of bedrock. The NW-SE lineament feature is expressed in the bedrock topography. The light contours are the surface topography. The sinkhole area is in the southeast corner.

with 2-D resistivity cross-sections, the vertical dipole map appears effective in portraying the character of the bedrock structure beneath the site. These geophysical illustrations are keys pieces of information for understanding the overall geologic setting of the site.

Three of the locations shown on Figure 5 (B-106, B-104, and B-112) were selected to evaluate the low resistivity lineament feature which the valley follows. Two locations, (B-107 and B-108) were selected to test low resistivity anomalies which appeared to connect with the lineament. These appeared to be heavily weathered zones connected to the main lineament. The remaining borings (B-101, B-111, and B-103) were selected to calibrate to the highest resistivity areas of the site. The three borings along Line 1200E (B-106, B-107, B-108) were also selected to allow remodeling of this key cross-section.

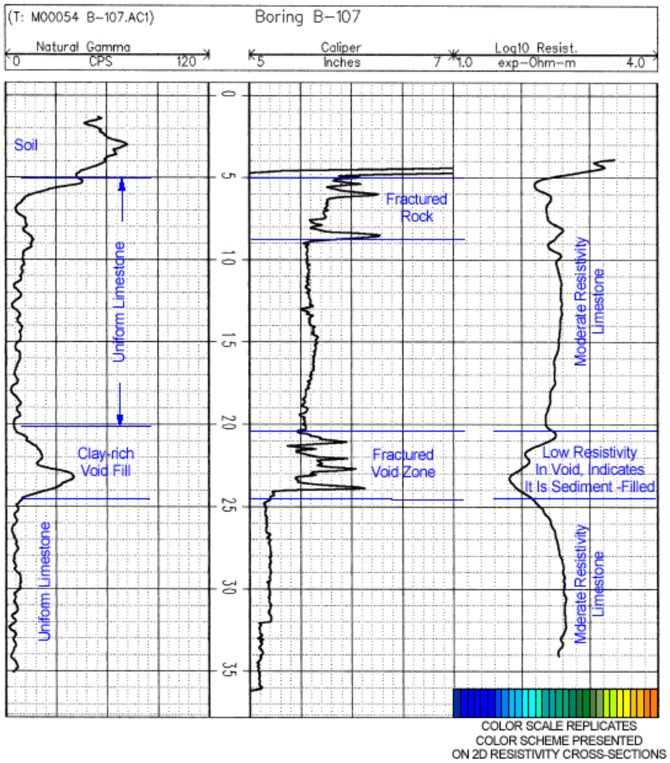


Figure 6. Geophysical log from Boring B-107. This is the center boring on Line 1200E (Figure 7). Natural gamma, left, clearly indicates soil and limestone as shown. Note the clay-filled void clearly detected by the 3-arm caliper (center). Limestone resistivity data was used as a constraint to remodel Line 1200E.

Field Activities

Auger and air percussion drilling were completed to provide direct access to the soil and bedrock for geophysical logging purposes. Geophysical logging was conducted in seven of the eight open borings shown on Figure 5 to provide not only accurate lithologic and depth-to-bedrock information, but also to provide 1) in-situ electrical resistivity data for calibration with existing surface geophysical data and 2) the locations and characteristics of fractures and voids. Three types of borehole geophysical logging were performed: natural gamma, electromagnetic conductivity, and three-arm caliper. These methods provided information about the lithologic conditions, existence of fractures and voids, and electrical resistivity readings for calibration with surface geophysical data. An example of one of the borehole geophysical logs from Boring B-107 is provided (Figure 6). The information from the geophysical logs was used to:

1) define the elevation of the bedrock surface (see bedrock elevation map superimposed on Figure 5 and also the top of bedrock profile on the reprocessed Line 1200E, Figure 7);
2) determine the competency of the limestone bedrock in evaluating the potential presence of highly fractured or weathered rock or voids;
3) integrate the borehole resistivity data into the previously mapped EM-34 resistivity and modeled 2-D resistivity data to calibrate the existing surface geophysical data; and
4) compare the borehole and surface geophysical data and resulting interpretations with the overall geologic setting (local and regional) to arrive at an interpretation of the geologic conditions at the site (Figure 8).

Data Processing and Interpretation

Creation of the bedrock elevation map

The bedrock elevation map shown on Figure 5 has revealed that a significant depression in the bedrock surface is present beneath the site. This valley only partially coincides with the topographic valley at the surface. It continues on a relatively straight course to the north-northwest, whereas the surface valley turns more to the west. This feature appears to be a significant bedrock fracture or fault zone. It has significant regional extent. This elevation map was created using the over 60 older borings drilled by the geotechnical engineer, the eight newer borings, and surface geophysical data.

Remodeling and Calibration of the 2-D resistivity Line 1200E

Line 1200E (Figure 7) was reprocessed to include the topographic data and was constrained using the three new borehole resistivity logs (B-106, B-107, and B-108) as shown on Figure 7. The geophysical logging indicated about two orders of variation in resistivity (10^1 to 10^3 ohm-meters). This new information helped subdue the severe modeling overshoot present in the initial, unconstrained resistivity data. Annotation was added to Line 1200E indicating a reasonable degree of confidence in the location of the top of bedrock, structural features (such as the NW-SE Lineament), ridges and troughs, and air or soil filled voids.

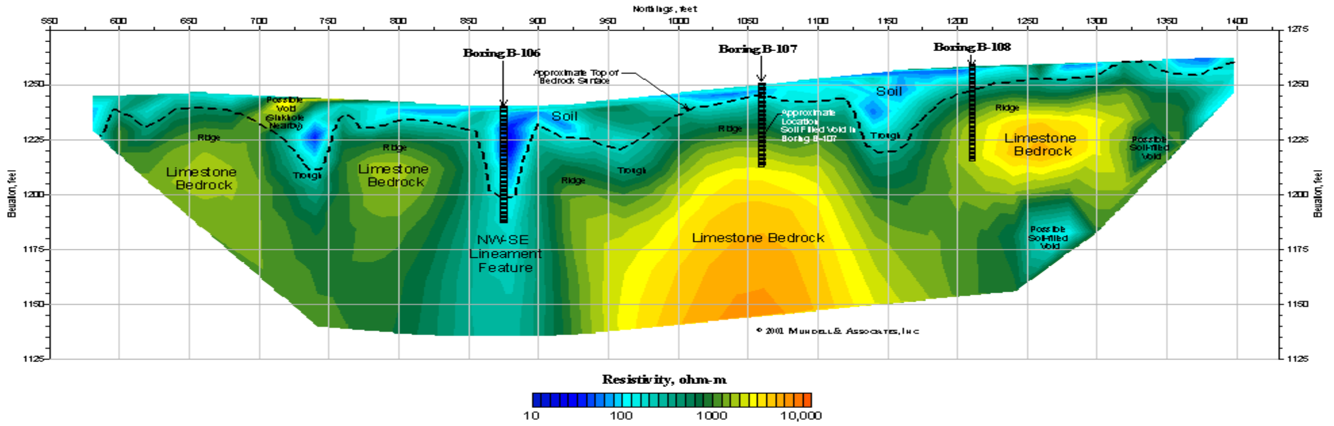


Figure 7. Reprocessed Line 1200E. Surface topography was added and resistivity values were constrained at the three boring locations shown. The resistivity overshoot in the initial modeling appears to have been reduced by incorporating the resistivity data from three borings. The undulating bedrock surface is quite apparent. A shallow high resistivity zone near 720N is labeled as a possible air filled void in soil. It is located very near the area of known sinkholes and is also near the intersection of the two lineaments. The NW-SE lineament feature is very prominent on this section. Note the low resistivity zone near 1250N to 1300N and at a depth of about 60 to 70 feet; it may be a soil filled void.

Development of a Overall Geologic Concept

Finally, the integrated interpretation of the EM-34 resistivity maps, 2-D resistivity cross sections, drilling observations and borehole geophysical data has resulted in the overall geologic concept for the site. This interpretation is portrayed on Figure 8. It has been observed that the site primarily consists of two large, limestone bedrock "blocks" clearly shown on Figure 8. A portion of the site, restricted to the southernmost area, is underlain by deep soils. Several dominant structural features are also apparent at the site, the presence of which has clearly controlled physical and chemical weathering of the limestone bedrock. First, a strong east-northeast fabric of pinnacles and grikes on the upper surface of the limestone blocks is very apparent. This fabric is clearly shown on the EM-34 resistivity map on Figures 3 and 5. This fabric consists of alternating high resistivity and low resistivity anomalies. The pinnacles and grikes are also annotated on Line 1200E (Figure 7).

The limestone bedrock blocks are divided in the center of the site and are bounded on the south end of the site by lineament features. The more regionally significant of the two lineaments is the NW-SE (northwest-southeast) Lineament shown in red crosshatch on Figure 8. This feature is clearly depicted both on the EM-34 resistivity map (Figures 3 and 5) and the 2-D resistivity cross-section (Figure 7).

A second, less distinct lineament, the NE-SW (northeast-southwest) Lineament is depicted on Figure 8 in a green crosshatch pattern. This lineament defines the southern boundary of the two largest limestone blocks. Geophysical data indicate this too is a deep running, highly weathered zone.

The transition zone between the lineament features and the bedrock blocks appears to be a complex, highly variable weathered zone. This overlap zone is the target for potential concern regarding the formation of karst features including voids. In this zone, the process of chemical weathering is interpreted to have had the potential to invade the bedrock laterally along the lineament sidewalls where it had access from the deeply weathered lineament zones. The drilling in these overlap zones, although limited in scope, did discover one relatively small void (Boring B-107, Figure 6). This void was about two feet in thickness and was filled with soil. Other soil-filled voids may be present in these zones as suggested by two labeled soil-filled voids shown on Figure 7 between the Northings of 1250N and 1350N.

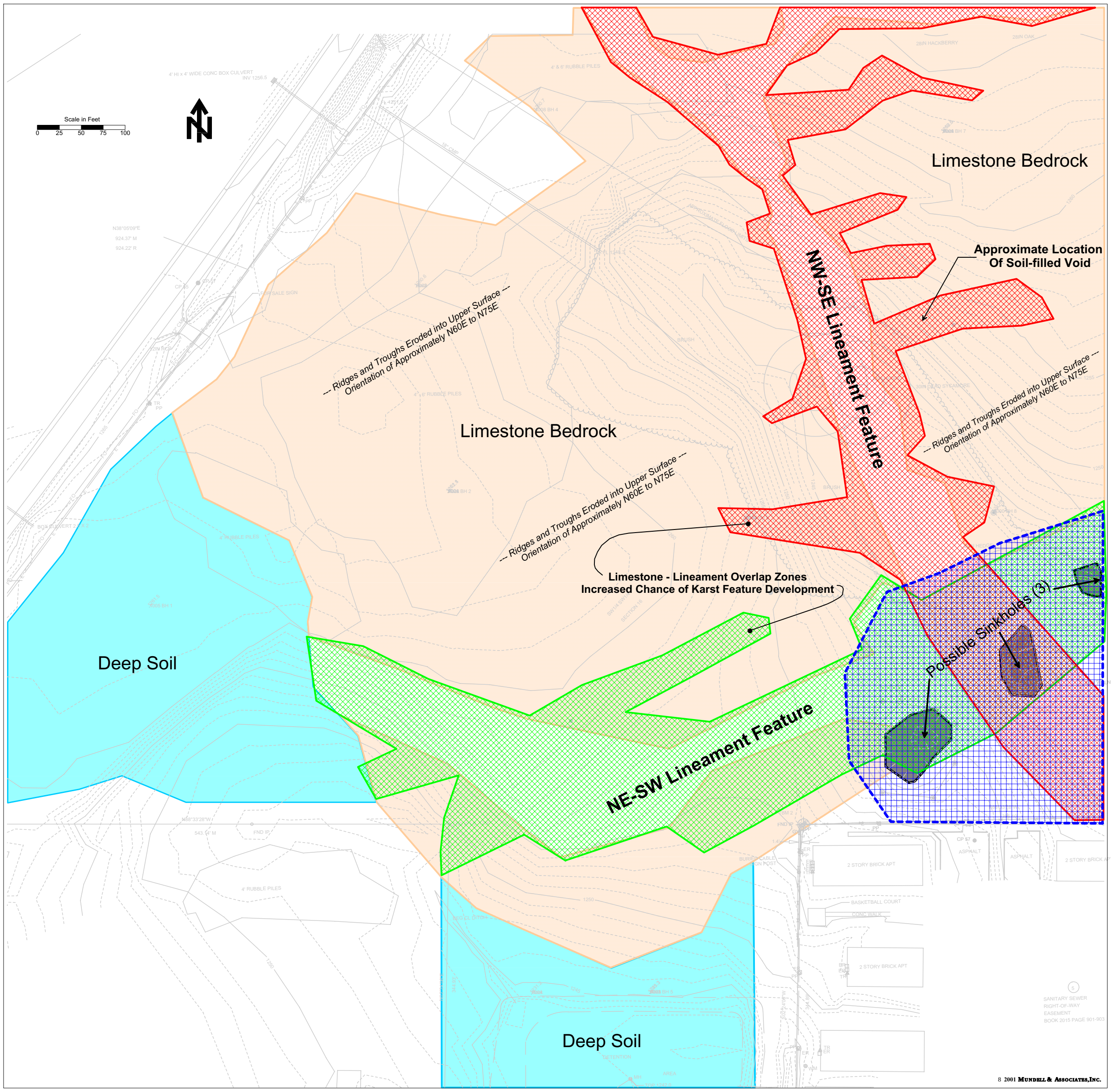
The intersection of the two lineament features in the southeast corner of the site appears to be the focus of contemporary soil transport. The precise mechanism for the formation of active sinkholes is not completely known, but it appears the sinkhole prone area shown on Figure 8 is at the head end of a losing stream that has progressively more extensive karst feature formation downstream. One such feature is a large sinkhole located about a mile southeast of the site. The site itself appears to be in an intermediate stage of karst activity. The process of developing an interconnecting network open void in the limestone bedrock does not appear to have begun except perhaps within the southeast corner of the site. This process will continue to propagate upstream over time as chemical and physical weathering continues.

Summary and Conclusions

The case history presented here is a real example of a collaborative effort between a geotechnical engineer and geophysical consultant. After conducting a preliminary geotechnical investigation, including over 60 soil borings, the geotechnical engineering prudently recommended to his client that a geophysical survey be conducted after he determined a reasonable likelihood that potentially critical karst conditions existed at the project site.

The geophysical consultant was confronted with the challenge of a short deadline, limited resources, and a large, 25-acre, heavily overgrown project site. A solution was required which conformed to these restrictions while still providing the geotechnical engineer and his client with an acceptable level of assurance that a reasonable effort had been made to detect critical karst features.

A combination of terrain conductivity mapping on a relatively tight spacing and 2-dimensional resistivity imaging, later calibrated with soil borings and geophysical logging, were implemented on this project. The resulting data were synthesized with regional data to develop a conceptual geologic model that was used as a tool to aid the geotechnical recommendations. The scale of the investigation was found to be appropriate by the geotechnical engineer, although the possibility of missing a small feature such as a soil pipe or void continued to exist.



Limestone Bedrock

🟧 Area underlain primarily by **Limestone Bedrock (***yellow* pattern). Bedrock surface is marked by ridges and troughs developed on its upper surface. Depth to bedrock generally ranges from 0 to 10 along ridges and can exceed 20 feet in troughs. Primary orientation of ridges and troughs is approximately N60E-75EE, secondary orientation is N30E-55EW.

Deep Soils

🟦 Area underlain primarily by **Deeply Developed Soils (***light blue* pattern). Drilling did not reach bedrock, therefore nature of underlying bedrock is unknown. Depth to rock appears to generally exceed 20-30 feet based on drilling and geophysical data.

Lineament Features

Areas observed to be underlain by one of two **Lineament Features** are shown in the ***red*** or ***green*** patterns shown at left. Both Lineaments are characterized by anomalously thick overburden above bedrock. Drilling has indicated up to 45 feet of soil above rock, and geophysical data suggests perhaps greater thicknesses. These zones appear to be relatively narrow, deeply weathered features.

🟥 **NW-SE Lineament Feature**

The NW-SE-oriented Lineament (***red*** pattern) has been observed to be a regionally significant feature, possibly a fault zone. Several large sinkholes are within about one mile of the site to the southeast along this Lineament. The orientation of the NW-SE Lineament is approximately N30E-50EW. The on-site sinkholes are found at the south end of this Lineament. This Lineament is expressed topographically on the southeast corner of the site, but is concealed on the northern portion of the site. Both geophysical and drilling data have shown this feature's existence.

🟩 **NE-SW Lineament Feature**

The second Lineament (***green*** pattern) is oriented NE-SW at its east end and has variable orientation on its west end. More subtle, this Lineament is primarily expressed in the geophysical data having little topographic expression.

Potentially Karst-prone Areas

Limestone-Lineament Overlap Zones

🟩 🟥 The overlap between areas where Limestone Bedrock (*yellow* pattern) is bounded by Lineament Features (***red*** or ***green*** pattern) may be **prone to the development of solution features** such as enlarged fractures or voids. Much of this overlap occurs where fingers of low resistivity project away from the main Lineament into the Limestone Bedrock. One such anomaly investigated with drilling encountered a soil-filled void (see Boring B-107, Figures 1,2 and 3).

Sinkhole Prone Area

▦ Area shown within this area appears to be at greatest risk of containing active sinkholes. There are perhaps up to three active sinkholes apparent in this area. This area lies at the intersection of the two Lineament Features. This intersection appears to be controling the creation of the sinkholes. Geophysical data suggests that this outlined area contains **anomalously high resistivity materials,** possibly indicating the presence of low density materials or void spaces. **This area should be evaluated further in greater detail if development is conducted here.**

Figure 8. Composite Geologic Interpretation Map.

Overall, the combination of the 10-meter horizontal and vertical dipole terrain conductivity maps proved very useful at this particular site in providing a sense of the pinnacle and grike texture. It also provided a qualitative idea of the relative depth to bedrock. Obviously the relatively thin soil mantle was critical to the quality of the terrain conductivity results. The terrain conductivity maps alone would provide an excellent "roadmap" for additional exploration. The 2-dimensional resistivity, especially after it was constrained by borehole geophysical data, provided an excellent visual representation of the subsurface features. If nothing else, it provided the client with a result that was very intuitive and easy to understand. The approach used was effective in developing a general understanding of where voids might form, but was probably too coarse to detect air filled voids in the soil mantle. Electrical methods have not proven to be effective enough for this purpose, at least to our satisfaction. Ultimately, based on these results, the geotechnical engineer was able to develop both a foundation design and construction verification plan that minimized the potential for structural distress due to potential void areas, as well as a stormwater drainage system that significantly reduced the likelihood of enhancing existing soil loss and weathering processes.

References

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