SUBSURFACE IMAGING OF KARST GEOLOGY FOR ENERGY INFRASTRUCTURE EXPANSION

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Abstract

The development of building infrastructure on top of karst geology always presents challenges and has the potential for catastrophic failure. Recently, an electrical substation located in southern Indiana known to sit atop potentially karstic limestone was scheduled to be expanded onto an adjacent 10-acre parcel. A standard preliminary geotechnical investigation consisting of 18 soil borings with three rock cores conducted across the parcel indicated that although the bedrock was slightly to moderately fractured, it was sufficiently competent to build upon. However, the presence of several active sinkholes across the parcel led the local electrical power company to request a more thorough, geophysical investigation of the bedrock. For this project, a preliminary terrain conductivity survey was performed to yield information regarding the thin residual soils and shallow bedrock, followed by two-dimensional resistivity profiling to detect any karst features deeper within the bedrock. The end result of the geophysical study gave the structural 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

It is commonly known by geotechnical and structural engineers that building on top of karst-prone limestone can prove disastrous if potentially hazardous features are not recognized prior to final design and construction, and dealt with appropriately. Given the recent interest and funding available to update and expand the nation's energy infrastructure, this preliminary due diligence is critical to the portions of the country affected by solution-prone limestone. As it is, southern Indiana is one of those areas. Recently, our company was contacted by a local electrical company in southern Indiana, to use geophysical methods to detect and map out karst features in the limestone bedrock beneath the proposed site of a power substation expansion. Prior to contacting us, another engineering consultant had recently performed a preliminary geotechnical investigation of the site consisting of advancing 18 random soil borings to bedrock, three of which were cored up to 10 feet into the bedrock. Although the rock cores indicated that the limestone in those areas were slightly to moderately fractured, the report concluded that soil and bedrock were sufficiently sound enough to build upon. However, an employee of the electrical company recalled that a cave had been detected during the construction of the original substation. Additionally, several active and developing sinkholes were present within the expansion area, just south of the proposed structure footings. For these reasons, the electrical company decided that a more in depth subsurface investigation was necessary.

Figure 1: Site Location Map. Ramsey is 20 miles west of Louisville, KY.

Site Description and Geology

The project site is located in Harrison County near the town of Ramsey, Indiana, approximately two hours due south of Indianapolis and thirty minutes west of Louisville, Kentucky (see Figure 1). At the time of the geophysical investigation, the site consisted of about 10 acres of agricultural land. There is approximately 20 feet of relief across the site, which slopes from west to east.

Ramsey, Indiana is located within the physiographic region known as the Mitchell Plateau. The soil in this part of the state is classified as the Baxter loam, and it is underlain by middle Mississippian limestone, specifically of the Sanders and Blue River Groups, which is highly susceptible to solutioning (Fenelon and Bobay, 1994). Karstification occurs 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. Karst, or karst geomorphology, is evidenced by numerous closed depressions, sink holes, karst windows or unroofed caves, springs, and cave openings, all of which are present in this portion of Indiana (Unterreiner, 2006). Within mature karst systems, surficial depressions are caused by the dissolving (or solutioning) of underlying carbonate rocks along existing joints and fracture systems that result in enlarged void spaces. Subsequently, the loss of shallow soils occurs as surface water infiltration is directed to these void spaces and the soil is swept into them through the resulting groundwater movement through fractures zones (see Figure 2).

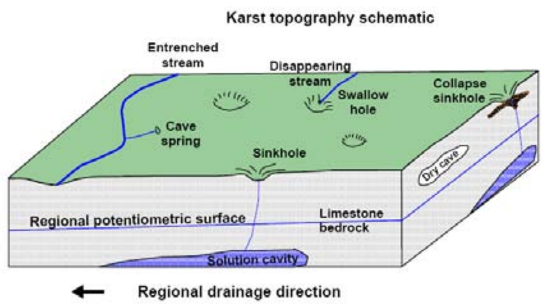

Figure 2. Karst Topography Features

Technical Approach

In cases such as this Site, where karst features are known to exist, geophysical mapping can provide insight into the locations of concealed features such as sinkholes, solution-enhanced fracture zones, and voids. In general, a variety of geophysical techniques can be applied to the mapping of subsurface karst features; however, certain methods, sensitive to a range of contrasting physical properties, can have attributes that make them more suitable than others depending on the site-specific conditions. Contrasting physical properties that typically are found to be useful for mapping soil and bedrock include electrical conductivity or resistivity, acoustic velocity, density, and magnetic susceptibility. Of these, electrical conductivity/resistivity has often been found to have the greatest range of contrast, and is often applicable to karst sites.

The technical approach used for the case history presented here is similar to the multi-step approach taken by Ahmed and Carpenter (2001) and Byer et al. (2002). 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, which could contain underconsolidated soils (*i.e.*, materials with high moisture content and low shear strength). Interpretation of the terrain conductivity data is then supplemented with two-dimensional electrical resistivity imaging (2-D ERI) within the context of the interpreted terrain conductivity data. Finally, the terrain conductivity and 2-dimensional resistivity data are interpreted together 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 (Byer et al., 2002). 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. A brief description of these two techniques is presented in the sections below.

Preliminary Terrain Conductivity Mapping

The approximate study area dimensions were 825 feet by 575 feet. Given the large area of the site (approximately 10 acres), it was determined that a preliminary conductivity survey would be conducted to delineate soil variations, yield insight into the upper most weathered bedrock layer, and guide the layout of the vertical resistivity profiles. For this investigation, a *Geonics EM-31* electromagnetic terrain conductivity meter was used. This instrument can gather apparent conductivity data at a relatively rapid pace without the need for direct (galvanic) ground contact, making it economical and efficient for covering large areas.

To assure that the *EM-31* was operating properly, five instrument checks were made at the start of the day. First, a battery check was made to ensure proper supply voltage over the duration of the survey. Second, a DC null adjustment was made to verify the zero position of the receiver circuitry. Third, a compensation check was made to verify the zero reading of the in-phase component. Fourth, a phase check was made to calibrate the conductivity reading. And finally, a sensitivity check was made to ensure that the instrument was reading as expected. No daily drift correction was necessary with this instrument.

Conductivity data was collected by securing the *EM-31* to a rigid plastic sledge and towing it behind an all terrain vehicle, collecting electrical conductivity data nearly continuously. *EM-31* data were collected along lines spaced approximately 1.5 to 3 meters (approximately 5 to 10 feet) apart with an in-line data point spacing of 0.3 to 1 meter (approximately 1 to 3 feet), depending on the speed of the instrument. Positioning data were provided by a *Trimble Ag114* global positioning system (GPS) receiver with real-time satellite based differential correction. GPS and conductivity data were simultaneously recorded in a handheld field data logger. The data stored in the data logger were in the form of apparent conductivity in milli-Siemens per meter (mS/m). However, this data was

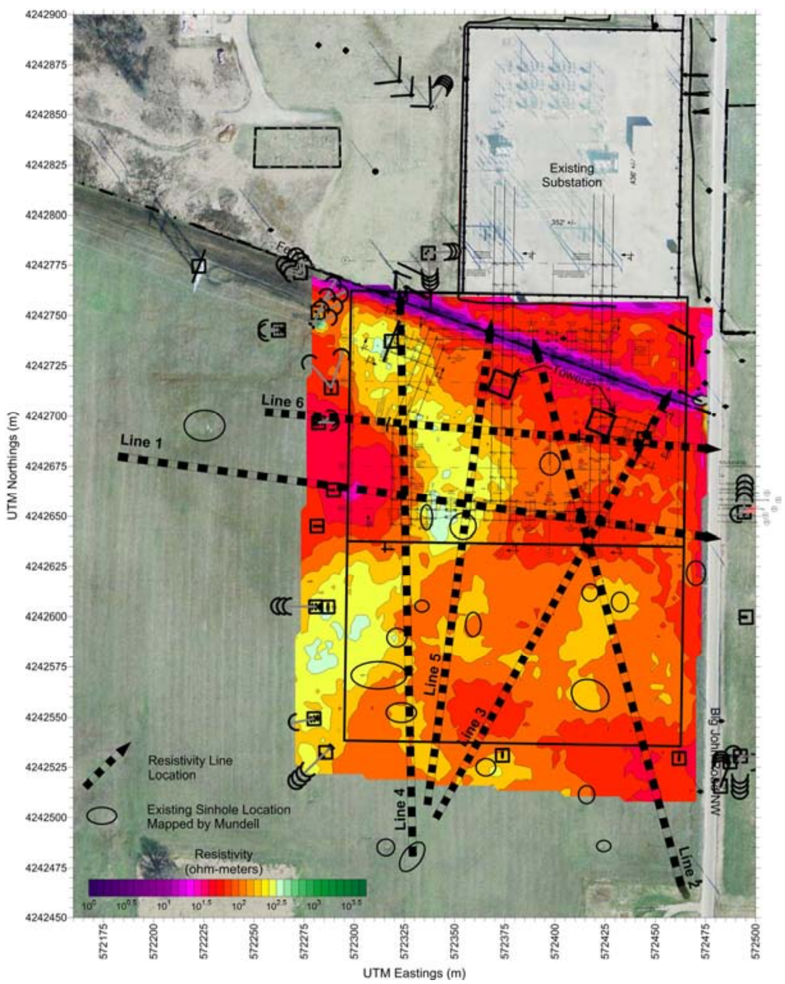

Figure 3: EM-31 Map. The data here are presented in ohm-meters, with a logarithmic color scale. The values detected range from 1 to 300 ohm-meters. A basemap of proposed substation features is overlying the EM-31 map.

later converted to apparent resistivity for mapping purposes and comparison to the 2-D ERI results by inverting the apparent conductivity data and multiplying by 1000. The resulting apparent resistivity data are in units of ohm-meters. Once the data were converted, they were imported into *Surfer* V*ersion 8.0* for contouring and plotting as a color-filled contour map of terrain resistivity (see Figure 3).

Two-Dimensional Electrical Resistivity Profiling

After the conductivity had been processed, revealing the variable, weathered-bedrock surface, the site was further investigated with 2-D ERI using a *Sting Resistivity Imaging System* from Advanced Geosciences, Inc. This method consists of recording direct measurements of the apparent electrical resistivity of subsurface materials *(i.e*., resistivity of homogeneous isotropic ground that would give the same voltage-current relationship as that measured) in a profile-type data set known as an apparent resistivity pseudo-section. Once the apparent resistivity data were collected, they were downloaded to a computer and were subsequently inverse-modeled using the software *EarthImager 2D v1.9.9* to obtain a cross-section of the "actual" resistivities of subsurface materials. This is accomplished through the process of generating a model resistivity cross-section, calculating the theoretical apparent resistivity pseudo-section that would result from such a model, and comparing the theoretical pseudo-section to the one collected in the field. The model is then altered through a number of iterations until the theoretical and field-collected pseudo-sections closely match each other. At this point the model is considered to be a reasonable estimation of the "actual" resistivities of the subsurface materials.

Electrical resistivity (and its inverse, conductivity) is one of the most widely varying of the physical properties of natural materials. Certain minerals, such as native metals and graphite, conduct electricity via the passage of electrons; however, electronic conduction is generally very rare in the subsurface. Most minerals and rocks are insulators, and electrical current preferentially travels through the water-filled pores in soils and rocks by the passage of the free ions in pore waters (*i.e*., ionic conduction). It thus follows that degree of saturation, interconnected porosity, and water chemistry (*i.e*., totally dissolved solids) are the major controlling variables of the resistivity of soils and rocks. In general, electrical resistivity directly varies with changes in these parameters. Fine-grained sediments, particularly clay-rich sediments such as glacial till, are excellent conductors of electricity, often much better than fresh water found in the pores of sand and gravel. Carbonate rocks (*i.e*., limestone and dolomite) are very electrically resistive when they are unfractured, but can have significantly lower resistivity values when fractured and/or solutioned.

For this geophysical investigation, a total of six (6) resistivity profiles were collected, utilizing both a 56 and a 60 electrode spread, and a dipole-dipole configuration to characterize the electrical properties of the upper 55 to 60 meters of the subsurface. It should be mentioned that resistivity cross sections are 2-dimensional representations of the general distribution of electrical resistivity in the 3-dimensional subsurface. Although there is no unique direct conversion from resistivity values to lithology, based on site knowledge, geometric shapes and relationships of various anomalies, and the observed ranges of resistivity values, reasonable geologic interpretations can be made. The interpretations of this survey are presented in the section below.

Interpretation

The *EM-31* results (Figure 3) show the apparent resistivity of the upper approximately 5 meters (approximately 16.5 feet) of the subsurface. The *EM-31* data is a reflection of the conditions in the relatively shallow subsurface materials (*e.g*., generally overlying residual soils, or shallow upper competent/weathered bedrock). Resistivity variations on this map reflect variations in the depth to bedrock as well as changes in porosity, moisture content, fracture density, clay content, and void space material. The lowest resistivity values, *i.e.*, approximately 45 ohm-meters and below, are interpreted as thicker soil layers that may also be higher in moisture content and/or clay and silt (presented as magenta to purple in color), except where metallic objects (fences and power line towers) have been noted. In upland areas these thicker soils are often moist, lower strength materials, which are not recommended for large structure foundations with high bearing pressures. The moderate resistivity values (45 to 130 ohm meters – red to orange in color) are interpreted to be thicker layers of coarser-grained clayey soils with an increased sand content. While this type of soil is typically preferable to build upon, it should be noted that these values occur in areas containing existing and developing sinkholes. This is likely because a large percentage of the fine-grained soils have been lost to the karst features. Finally, the moderate to high resistivity values, *i.e.* approximately 130 to 300 ohm meters (yellow to light green) are interpreted as the uppermost weathered bedrock layer. Essentially, these values show where the bedrock is shallowest across the site.

The six inverted and interpreted 2-D resistivity profiles collected are summarized on Figure 4. The resistivity values modeled, range from 1 (purple in color) to 4,500 Ohm-meters (dark green). In

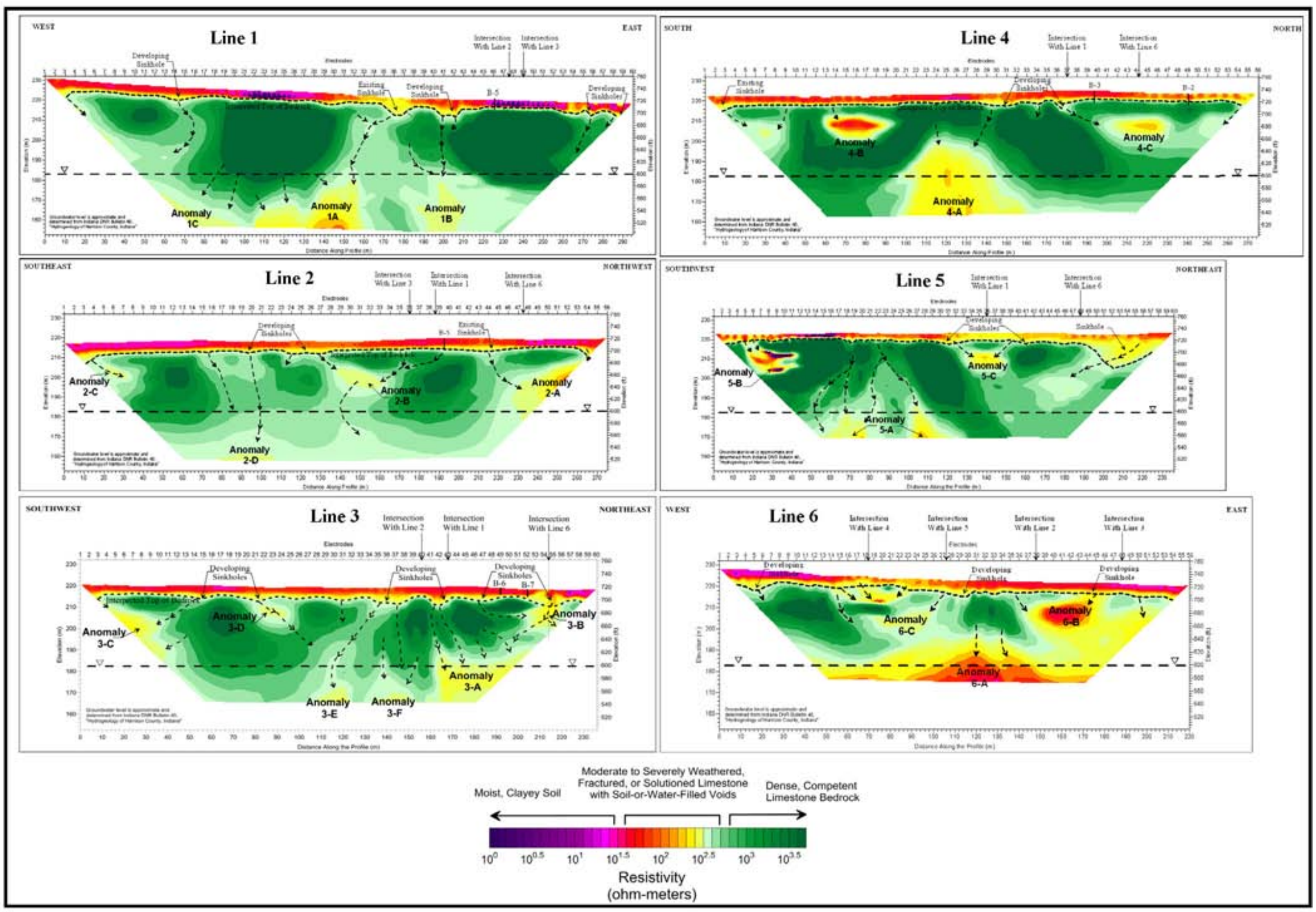

Figure 4: Vertical Resistivity Profiles. The data here are presented in ohm-meters, with a logarithmic color scale. The short dashed lines show the interpreted top of bedrock surface, whereas the longer dashed lines with arrows show possible flow pathways through the rock.

general, the cross-sections are quite similar: the upper 3 to 5 meters (10 to 16 feet) consists of an inhomogeneous assortment of low (purple to pink) to moderately high (red to yellow) resistivity materials which are correspondingly interpreted as, from low to high, clay and silt to coarse sand and gravel. These unconsolidated materials lie directly on top of a moderate to high resistivity material, which is interpreted to be the Paleozoic bedrock. The highest resistivity bedrock is interpreted to be relatively competent, massive limestone or dolostone bedrock (dark green color), while the moderately high resistivity bedrock (red to light green color) is likely fractured carbonate bedrock, with the lower end values possibly indicating soil and/or water filled features. It should be noted that the lower resistivity soils appear to overlie the competent rock, while the higher resistivity soils generally overlie existing and developing sinkholes. This supports the theory implied by the conductivity data, that the finer-grained soils across the site are being lost to subsurface features, which suggests active karst development.

After the individual resistivity profiles were processed, they were compiled into a three-dimensional data set, and several lateral (*i.e.*, constant elevation) resistivity slice maps were generated in attempts to better understand the lateral and vertical location of active and developing karst features, and how they relate to the proposed building plans. Resistivity slices taken at elevations 700 feet, 680 feet, 660 feet, 640 feet, 620 feet, and 600 feet elevations are presented respectively as Figure 5. A comparison of these slices reveals that while the majority of the substation expansion appears to overlie mostly competent bedrock, approximately 20 to 30 percent of the proposed structures lie on top of highly weathered/fractured bedrock. In addition to the proposed structures, one of the existing power line towers (located in the northeast portion of the

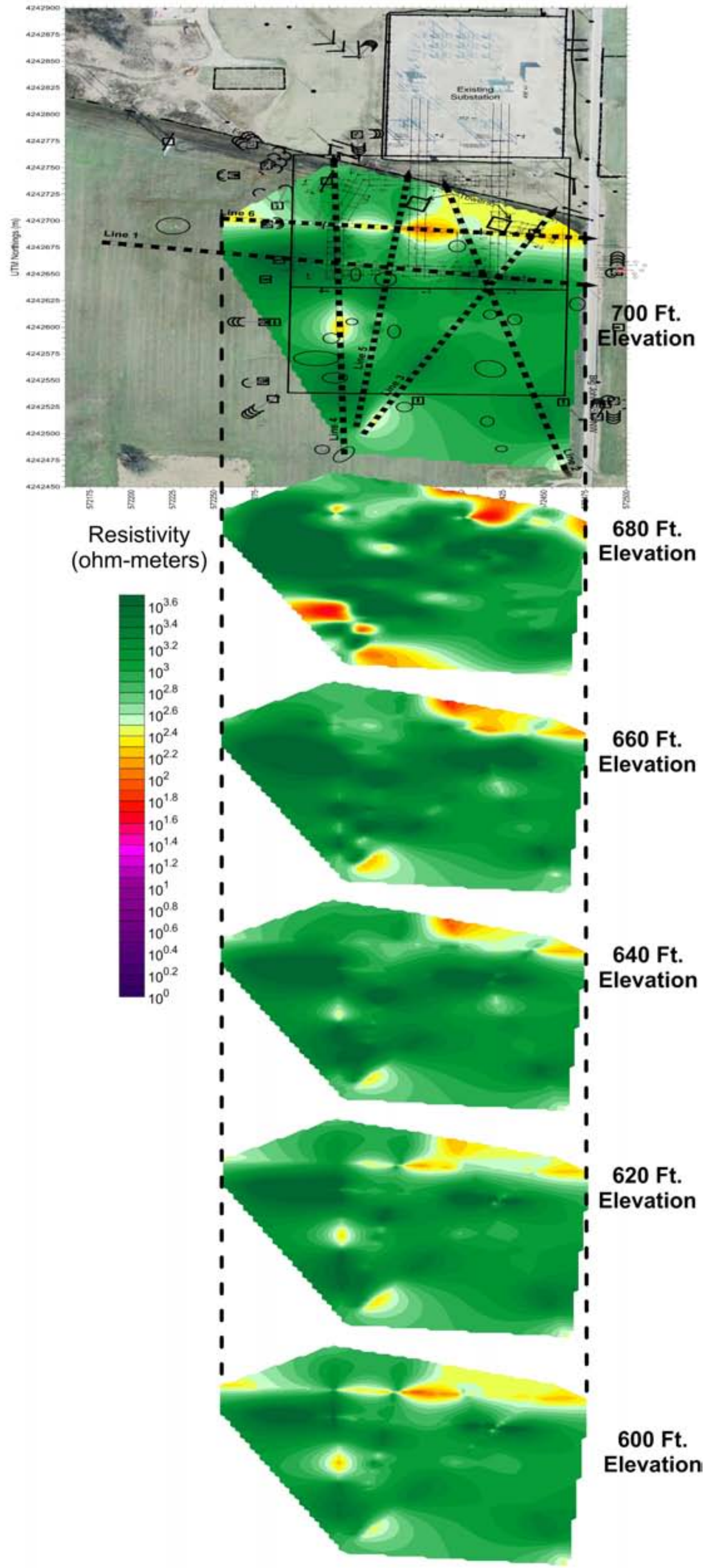

Figure 5: Constant Elevation Resistivity Slices. The data here are presented in ohm-meters, with a logarithmic color scale.

survey area) is located directly on top the most pronounced karst feature on the site.

Finally, in addition to the slice maps, all of the data gathered across the site was utilized to generate a map summarizing the degree of karst development across the site (Figure 6). As shown on the figure, the site has been segregated into the following classifications: low, shallow karst development (consists of dense, competent limestone likely present beneath residual clay soils at depths of less than 25 ft); moderate, shallow karst development (with weathered/ fractured/solutioned limestone beneath residual clayey/sandier soils at depths of less than 25 ft); and severe shallow karst development (characterized by severely weathered/fractured/solutioned limestone with clay soil in-fill and/or potential for small voids within the upper 25 ft). Essentially, this map showed the client which portions of the proposed expansion project were most susceptible to failure and required additional engineering measures to ensure the stability of the structures.

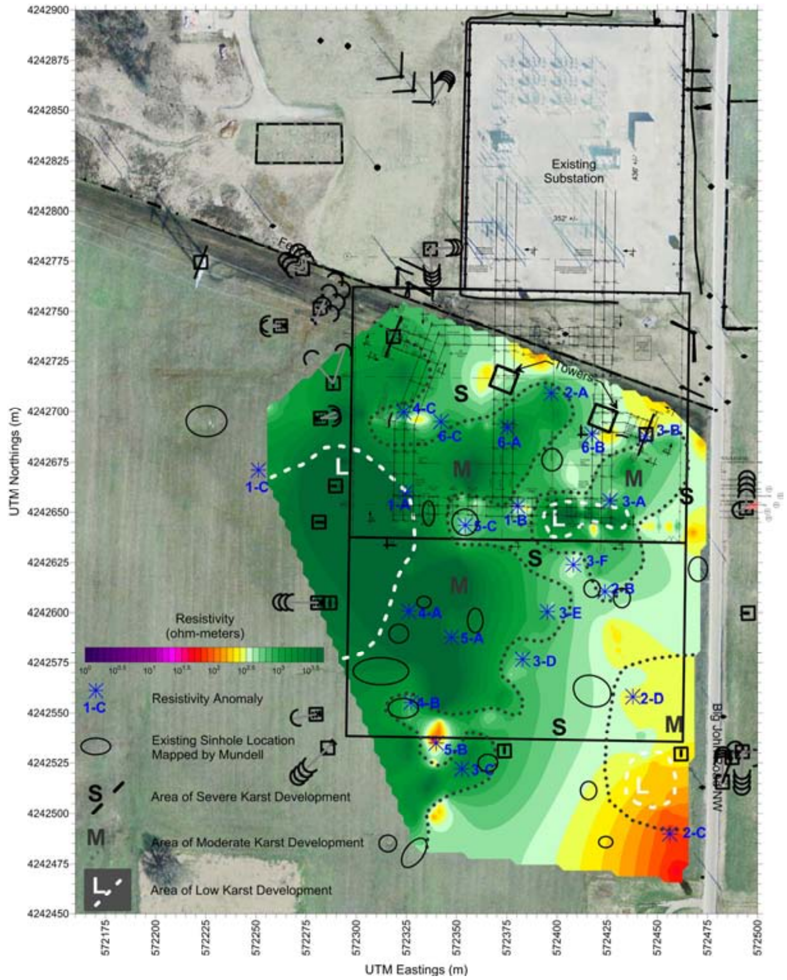

Figure 6: Karst Development Summary Map. This map summarizes the level of karst development across the site. As before, the data here are presented in ohm-meters, with a logarithmic color scale.

Summary and Conclusions

The geophysical consultant was confronted with the challenge of limited resources and a large, 10-acre project site. A solution was required which conformed to these restrictions while still providing the electrical power company with an acceptable level of assurance that a reasonable effort had been made to detect critical karst features.

To provide this assurance to the client, a combination of terrain conductivity mapping on a relatively tight spacing and 2D-ERI 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 company and the structural engineer responsible for the expansion project.

In conclusion, several key observations were provided to the client regarding the site in relation to the possibility of infrastructure expansion. First, the site is indicative of a typical highly-developed, karst terrain, with nineteen (19) sinkholes observed at the surface over the survey area. The position of the observed sinkholes correlated well with the conductivity and resistivity data. Also, these observed sinkholes appeared to be in active development, based on the detected weathered/solutioned zones emanating from them leading to deeper karst features, as well as the evidence of shallow fine-grained soil loss. While a substantial area of the proposed structural foundation features appeared to be positioned on top of competent or moderately weathered bedrock, several areas needed to be further examined and redesigned for the possibility of loss of support or the need for substantial grouting measures. Had the client not realized these shortcomings in the foundation support from the benefit of a preliminary geophysical survey, expansion of the infrastructure without regard to these conditions could have lead to a catastrophic foundation failure.

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