Geophysical Methods to Map Subsurface Evaporite Features to Aid Roadway Geometric Design

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ABSTRACT

Surface sinks, distressed highway sections, voids and evaporite bedrock with variable weathering have complicated highway design for the Oklahoma Department of Transportation (ODOT) in western Oklahoma. ODOT contracted with Terracon Consultants and Zonge Geosciences to collect approximately 45,000 linear feet of Direct Current Electrical Resistivity Imaging (ERI) data along Highway US-412 in Major County near Woodward, Oklahoma. The data was collected, using the Dipole-Dipole technique, to aid the design and construction efforts by identifying and discriminating between sections of highway underlain by solid gypsum or gypsum containing voids (resistivity > 1000 ohm-meters) and sections containing combinations of claystone and weathered gypsum (resistivity <100 ohm-meters).

Initial geophysical results were used to locate 18 confirming borings and identify the need and locations of additional geophysical testing. Borehole data correlated with the resistivity models and allowed for the assignment of resistivity ranges to specific lithologies which became the basis of all data interpretation for the geophysical survey.

The results presented here show that ERI offers an accurate and cost-effective approach to mapping lateral and vertical variations in material properties that can be directly associated with lithology. This can help alleviate common issues confronted when making geologic interpretations based on limited data from widely spaced borings. Two useful generalizations can be drawn about this specific project: 1) the highest values of resistivity more often correlate with gypsum hosting numerous smaller (0.5-1.5 feet diameter) voids than with large voids, and 2) large sections of the surveyed area (several 1,000s of feet) along US-412 are underlain by clay, weathered gypsum and gypsum-clay as confirmed by the borings, and will not likely pose many issues with regards to required mitigation efforts.

In summary, the ERI geophysical technique, as confirmed by the borings, successfully separated the sections of highway into distinct areas underlain by claystone and weathered gypsum and sections with gypsum dissolution features requiring different mitigation tactics. Success of the geophysical program can be related to a well integrated geologic, geotechnical and engineering program where ODOT, Terracon and Zonge personnel worked closely together to assess the subsurface data.

The results of the geophysical survey and boring program are being used in the final roadway design process to minimize the potential of sinkholes or caverns and the resultant impact on the new roadway construction. With the ERI and boring results delineating between those areas having gypsum rock and those areas not having gypsum rock, the design team has been able to focus attention on those portions of the alignment with existing or potential solution cavities. Thus, the design challenge is now on horizontal and vertical alignment of the highway and minimizing cut depths into the subsurface profiles that have gypsum rock and minimizing water seepage into the ground in those same areas.
INTRODUCTION

ODOT wants to modify both the vertical and horizontal alignment of two portions of US-412 in Major County, Oklahoma. The highway alignment areas include a section which extends from the Major/Woodward County Line eastward approximately 10,110 feet and a second section which extends from approximately 2,325 feet east of the US-412 and US-281 Junction, eastward approximately 9,000 feet (Figure 1).

Figure 1, US-412 Study Areas

Initially, the goal was to increase capacity by changing the highway from two-lanes to four-lanes. Along the western section of the study area, the two new lanes were to be offset to the north of the existing lanes. The eastern section of highway alignment was planned to include two new lanes south of the existing highway. Sight distance requirements required the design of deep cuts and fills.

This part of western Oklahoma is characterized by surface sinks, distressed highway sections, voids and exposed evaporate bedrock with variable weathering, which, historically, have been shown to impact the long-term performance of highway projects. Large systems of caverns are known to exist in this part of Oklahoma, with at least one known cave extending beneath US-412. As rainwater and groundwater run through fractures in the rock and between rock layers, dissolution of gypsum results in widening fractures, weakened sections of highly weathered material, large caverns and sinkholes due to the removal of materials that previously supported overlying rock and soils.
A geophysical survey program was designed for this project with the intent to map the lateral and vertical extents of the gypsum units associated with the dissolution features to help ODOT mitigate possible adverse impacts on the planned highway expansion projects. Terracon Consultants, Inc. (Terracon) teamed with Zonge Geosciences, Inc. (Zonge) for electrical resistivity (ER) geophysical surveying. In addition to the geophysical surveying, 18 borings were drilled to calibrate, or “ground-truth”, the geophysical results to physical subsurface conditions and to provide geotechnical information for design and construction of both cuts and fills along the highway alignment.

ER surveying is a geophysical technique which measures the electrical resistivity of the subsurface which is then correlated to subsurface geology and structure as determined with geotechnical borings. ER surveying employs two electrode pairs, one pair providing the electrical source (current electrodes) while the second pair measures the electric potential between the electrodes (measurement electrodes). Once measurements are obtained, they are processed to account for the array geometry (electrode arrangement) and other factors associated with data acquisition (e.g., topography, culture, etc.). Finally, mathematical inversion of an entire data set is performed, and the result is a two-dimensional (2D) earth model of the subsurface electrical resistivity structure; or, an electrical cross-section. Information obtained from boreholes is then used to correlate resistivity structure to lithologies and geologic structure.

Work for this project included:

- Field reconnaissance
- ER geophysical surveying along two lines at both US-412 projects
- Evaluation of preliminary geophysical results
- Consultation with ODOT to select additional ER survey and geotechnical confirmation boring locations
- Additional ER surveying
- Drill confirmation borings
- Synthesize ER and boring information into comprehensive geological interpretation

**SITE GEOLOGY**

Based on information published in the ODOT manual, “Engineering Classification of Geologic Materials, Division Six”, the project sites are underlain by two geologic units.

The Flowerpot Unit consists predominantly of reddish-brown, blocky, silty clay shale with a few thin sandstone, siltstone, and dolomite beds. Topographically, the Flowerpot Unit generally forms broad flats and gently rolling hills. The upper portion forms the steep slopes of scarps and buttes capped by gypsums of the overlying Blaine Unit.

The Blaine Unit consists of three prominent gypsum beds separated by red-brown shales which are locally gypsiferous. Topographically, the Blaine Unit forms the most pronounced
escarpments in western Oklahoma. The thick gypsum beds form ledges that extend the entire length of the outcrop of the Blaine Unit.

Underlying the resistant gypsums of the Blaine Unit are the weakly resistant shales of the Flowerpot Unit. The shales erode much faster than the gypsums, thus leaving an escarpment that is several feet higher than the near level terrain of the Flowerpot Unit. Isolated buttes and highly dissected canyons are common along the outcrop contact of the two units.

Of particular concern to the design and construction of the upgrades to US-412 is the excavatability of the Blaine Unit and the fact that the gypsum is prone to formation of dissolution cavities when exposed to flowing water.

GEOPHYSICAL SURVEYS

Knowledge of the subsurface material properties is critical to the engineering and construction phases of any highway project. The gypsum formations and dissolution caverns that extend beneath the highway in this part of the State extenuates the need for a more detailed, or continuous, analysis of the subsurface stratigraphy along the highway alignment.

Field Reconnaissance

The field reconnaissance included visual observation of the geophysical survey areas via vehicle and foot. Using direct observation, geologic maps, topographic maps, and aerial photos, areas that could potentially contain subsurface voids, such as those shown in Figure 2, were identified. Additionally, land access, potential worker safety, and general project logistics/coordination concerns were identified and addressed.

Figure 2, Small Surface Void in Cut Section of HW-412
Electrical Resistivity Survey

The ER geophysical survey design for the US-412 projects (West Section and East Section) included initially acquiring ER data along two lines, one located along the approximate new road alignment, and one located adjacent to the existing roadway (Rittger, et. al, 2008). For the US-412 West Section, ER data was collected along the existing roadway and approximately 150 feet north along the planned new roadway alignment. For the US-412 East Section, ER data was collected along the existing roadway and approximately 150 South along the planned road alignment.

The geophysical technique utilized for this project’s ER survey is referred to as the Double-dipole, or more commonly, the dipole-dipole technique (Telford et. al., 1976). As shown in Figure 3, in the dipole-dipole electrode configuration, a controlled electrical signal is transmitted into the ground via a grounded dipole consisting of two current electrodes (A and B). At varying distances from the midpoint of the current dipole, the electrical potential drop is measured and recorded at a different grounded dipole, called a receiver or potential dipole (M and N). This potential difference measured by the receiver dipole is due to the electric field created by the source current dipole. For this survey, an axial (or polar) dipole configuration was used, where the receiver dipole is in-line with the transmitter dipole (Al’pin, 1966).

![Figure 3, electrode configuration for the dipole-dipole DC resistivity technique](image)

Both the current and potential dipoles have two electrodes with constant spacing, referred to as the “a” spacing, and the distance between the transmitting and receiving dipoles is varied by multiples of “a”. Here, “n” is normally an integer value between 1 and 6. For this survey, an a-spacing of 20 feet was used.

The main material property of earth materials measured by electrical methods is resistivity ($\rho$), which is the reciprocal of conductivity ($\sigma$). Electrical resistivity is a quantitative measure of how difficult it is to send current through a material.

Variations in subsurface porosity, fluid content, fluid chemistry, permeability and soil or rock type all affect resistivity measurements. Cultural features (i.e., man-made items) such as fencing, power lines, and pipelines can also significantly affect resistivity measurements if not properly insulated from the ground or adequately avoided.

Ohm’s Law states that the ratio of the measured potential drop across the receiver dipole (M and N) to the measured output current across the transmitter dipole (A and B) yields the apparent resistivity (ohm-meters) at a certain point below the array.
Apparent resistivity is an average value for the non-homogeneous volume sampled by each measurement, and does not necessarily represent the true resistivity of earth materials at a certain lateral location or depth (Abraham, et al., 2004). This is the raw data to be modeled in order to obtain a true resistivity model of the earth below the dipoles.

As depicted in Figure 4, each measured and calculated apparent resistivity value is plotted at the center-point (or station) between the two dipoles and at a depth equal to the “n” value to create a pseudo-section. The pseudo-section is a generalized way to plot data coverage and quickly detect major anomalous readings prior to processing.

![Figure 4, Sequence of data collection in a dipole-dipole ER survey](image)

The instrumentation used to perform this geophysical survey was the Zonge Electrical Tomography Acquisition (ZETA) system produced by Zonge Engineering and Research Organization, Inc.

The first order of business in developing the field program was to optimize the data quality by testing various station spacing, electrode setup, currents, and filters. The optimization process resulted in an ER station spacing of 10 feet. There is an inherent balance between station spacing, depth of investigation, and lateral resolution. Larger station spacing would result in deeper depth of investigation but at a loss of lateral resolution. Preliminary field testing indicated that 10 feet spacing would provide a nominal depth of investigation of 60 feet or greater while maintaining good resolution of expected anomalies.

Production mode ER data collection was conducted immediately after parameter optimization. Initially, ER data was collected along 38,220 feet of test alignment. Relative elevations were recorded at every station (electrode) using a hand level and stadia-rod, and these elevations were converted to absolute elevations via tying to survey marks.

After preliminary processing and interpretation, Terracon and Zonge met with ODOT to review the results, identify areas for additional ER data collection, and identify confirmation borehole locations. Fifteen locations were identified as areas requiring additional ER geophysical surveying. These areas were typically selected because potential horizontal highway
alignment reconfiguration would bring the new alignment outside the boundaries of the initial survey or to further track a potential karst feature that was identified in the initial survey.

Additional ER geophysical surveying was conducted, resulting in collection of an additional 6,580 feet of ER data. The more focused additional ER surveying was conducted along approximately 34% of the 19,110 feet of highway alignment.

During ZETA data acquisition, multiple waveforms are stacked and averaged to reduce random noise in the data blocks. All data blocks are repeated at least twice to establish data repeatability. All individual blocks are recorded and saved digitally, along with standard error of the mean (SEM) values. The receiver operator monitors data quality in the field, and contact resistance issues are resolved and data acquisition is repeated if necessary. Data quality for this project ranged from fair to excellent with respect to SEM and block repeatability for ZETA.

Processing for ER data acquired using the ZETA system was performed using proprietary software developed by Zonge.

Smooth-model inversion mathematically back-calculates (or inverts) from the measured data to determine a likely distribution of true resistivity values. Comparison of the observed field data and the calculated pseudo-section plots is a useful method for evaluating how well the mathematical model fits the observed data. The results of the smooth-model inversion are intentionally gradational, rather than showing abrupt, blocky changes in the subsurface. The inversion results should not be considered a unique solution, and some ambiguity remains in any mathematical representation of the data. Confidence in any interpretation increases with corroborating information.

Confirmation Borings

Preliminary ER results were reviewed by Zonge, Terracon, and ODOT to determine boring locations to assist in the interpretation of the geophysical data. The objective of the geotechnical boring program was to provide geophysical ground-truthing and to provide preliminary geotechnical information for the planned road construction. The geophysical ground-truthing involves correlating lithology and geotechnical information obtained from the boreholes to the ER results. The geotechnical information includes standard penetration value (N) for soils and percent recovery (REC) and rock quality designation (RQD), compressive strength, and elastic modulus (E) values for rock cores.

The boreholes were advanced using rotary wash methods with both truck-mounted and all-terrain drilling vehicles. Representative soil samples were obtained by the split barrel sampling procedure in accordance with the appropriate ASTM designation. Rock cores were obtained with a standard diamond-bit, double-barrel, core-barrel.
The soil and rock core samples obtained were logged for lithology (and/or lack of lithology if voids were encountered). Table 1 shows the locations and results of the geotechnical borings.

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Purpose</th>
<th>Completion Depth (feet)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>WEST AREA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-1</td>
<td>54+500 (150' North)</td>
<td>Geotech</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>B-2</td>
<td>54+810 (150' North)</td>
<td>Void and Geotech</td>
<td>25</td>
<td>Void Detected 11 to 13', then small voids to 14' bgs</td>
</tr>
<tr>
<td>B-3</td>
<td>55+017 (150' North)</td>
<td>Void and Geotech</td>
<td>38</td>
<td>Voids Detected between 22-24, 25-26 and 28-35' bgs</td>
</tr>
<tr>
<td>B-5</td>
<td>55+210 (85' North)</td>
<td>Void and Geotech</td>
<td>40</td>
<td>Small Voids between 15 22' bgs, water loss @ bgs</td>
</tr>
<tr>
<td>B-6</td>
<td>55+290 (20' North)</td>
<td>Void and Geotech</td>
<td>40</td>
<td>Small Voids @ about 22.5' bgs, water loss @ 9.5' bgs</td>
</tr>
<tr>
<td>B-7</td>
<td>55+450 (146' North)</td>
<td>Void and Geotech</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>B-8</td>
<td>55+720 (150' North)</td>
<td>Void and Geotech</td>
<td>36</td>
<td>Small Void @ 9.5' bgs, water loss @ 9.5' bgs</td>
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<tr>
<td>B-10</td>
<td>55+850 (75' North)</td>
<td>Void and Geotech</td>
<td>30</td>
<td>Water loss @ 14' bgs</td>
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<tr>
<td>B-9</td>
<td>56+035 (150' North)</td>
<td>Void and Geotech</td>
<td>42</td>
<td>Water loss @ 4.5'</td>
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<tr>
<td>B-11</td>
<td>56+520 (85' North)</td>
<td>Void and Geotech</td>
<td>35</td>
<td>Voids from 32-33.5' bgs</td>
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<tr>
<td>B-12</td>
<td>56+680 (150' North)</td>
<td>Void and Geotech</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>EAST AREA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-13</td>
<td>2046+050 (150' South)</td>
<td>Void and Geotech</td>
<td>36</td>
<td>Water loss @ 12.7' bgs</td>
</tr>
<tr>
<td>B-14</td>
<td>2047+000 (85' South)</td>
<td>Void and Geotech</td>
<td>34</td>
<td>Small Voids 19-21' bgs, water loss @ 21' bgs</td>
</tr>
<tr>
<td>B-15</td>
<td>2050+047 (150' )</td>
<td>Void and Geotech</td>
<td>13.5</td>
<td>Abandoned Due to Void @ about 13.5' bgs</td>
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<td>B-15A</td>
<td>2050+050 (150' )</td>
<td>Void and Geotech</td>
<td>64</td>
<td></td>
</tr>
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<td>B-16</td>
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<td></td>
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<tr>
<td>B-17</td>
<td>2079+000 (150' )</td>
<td>Void and Geotech</td>
<td>55</td>
<td>Small Voids from about 42' bgs</td>
</tr>
</tbody>
</table>

Table 1, Geotechnical Boring Locations and Findings

Geological Interpretation

After the 18 borings were completed, correlations were made between lithology as determined from the geotechnical borings and calculated resistivity values in the final models. This allowed for the assignment of a range of resistivity values expected for a given lithology. The three main materials encountered in the 18 borings were: 1) clay and clay/weathered-gypsum mixtures, 2) gypsum, and 3) large voids and highly fractured gypsum with many small voids.
Once ground-truthing of the models was complete, the ranges of resistivities within a given material were plotted, and are presented on Figure 5.

**Figure 5, Correlation Between Lithologic Units and Resistivity**

Each of these three material types correspond to a range of resistivities, and a unique color was assigned for each range on the color scale shown in Figure 6. This color scale was used for all final models, and it became the foundation of all interpretations for this project. The letters “C” and “G” and “V” were annotated on the color scales of all final models to indicate the interpreted lithologies.

**Figure 6, Resistivity Color Scales**
The final interpretation of the geophysical data and geotechnical borings were presented in 2D figures (electrical cross-sections), such as shown on Figure 7. These figures offer a pictorial representation of the boundaries of materials with potential karst features and those of clay and weathered shale.

**Figure 7, Example 2D Earth Models from ERI surveys**

**DESIGN RECOMMENDATIONS**

A total of approximately 45,000 feet of ER geophysical surveying was conducted and 2D models of the subsurface ER structure were prepared. Based on the ER results, the geophysical design team reached the following conclusions.

First, there are two areas of particular concern for encountering void features in the western section of US-412. One section is about 1,000 feet in length, and the second area is about 1,300 feet in length. Three other shorter sections of lesser concern were also encountered. One of these was encountered in the western section. That area is about 300 feet long. The other two lesser areas are in the east section. One is 800 feet long and the second is 500 feet long.

Second, depths to potential voids in the two areas of particular concern range from immediately below the ground surface to approximately 20 feet below ground surface. The background electrical resistivities in these areas are suggestive of weathered rock, implying that in these areas, the mechanical competency should be addressed for highway construction.

One significant observation is that many of the confirmation boreholes were specifically located to encounter open voids and only one boring encountered a significant (greater than 3 feet) open void. Thus, in the final design phase a much greater number of boreholes will be
drilled for statistically meaningful results. Based on the data gathered, it appears that most of the voids in the project areas are rubble filled. Although the geophysical methods successfully identified voids, in this area the difference in geophysical signature between rubble filled and an open void is small. If surface runoff water can be routed around areas with rubble filled voids, the risk of damage to the highway after construction is lowered.

Roadway construction in known karst formation areas requires that roadway embankments and cut sections be designed so that the impact of the karst formations on the roadway will be lessened or eliminated. Avoidance measures and some combination of drainage and/or bridging methods are usually the best steps to take in a proactive approach (Moore, 2006).

Subsurface void development in known karst formations is generally due to dissolution of materials from surface storm water runoff and/or groundwater flow, both during and after construction. Increased stormwater runoff can result in development of new void features or exacerbate existing conditions. Thus, surface storm water runoff must be routed away from areas identified as having voids, potential voids, or rubble filled voids. Studies (Moore, 1987, 2003) show that the majority of collapse-type karst problems occur in unlined ditches. Unlined ditches are typically sodded at best, and have gradients of less than 3 percent, and often, less than 1 percent. Ditch liners can include Portland cement concrete, asphalt pavement, or 60 mil PVC or geomembrane material. In addition, the final design must consider curbs for embankment sections to channel deep water from running off the edge of the pavement surface. Lined ditches should be strategically utilized to minimize ponding of rainwater and minimize the potential of rainwater to erode soil cover, exposing potentially erodible gypsum rock.

Those areas identified as having sinkholes or subsidence can be remediated for roadway use by bridging over the affected area to provide adequate stability to the roadway. Various approaches to bridging have included conventional bridge spans supported on foundation elements founded on solid bedrock, rip-rap backfill, rock pads, grouting of the void or subsided area, concrete slabs, and geogrids (Moore, 2006).

Rock pads can be constructed at the base of embankment fill to bridge depressions and sinkholes. Typically, the rock pads include large native non-degradeable stone (rip-rap) and or broken concrete. Such open graded mixtures of rock and/or broken concrete provide stability and drainage to the roadway fill (Moore, 2006).

Both horizontal and vertical alignment changes can minimize the impact of the new roadway to know karst formation areas. For example consideration can be given to the use of a passing lane through the steeper hills containing karst formations, instead of a wider 4-lane divided section. Such an alignment will minimize the amount of cut into the gypsum rock identified in the geophysical survey and confirmed with the soil borings. Similarly, the vertical grade through the hills with gypsum rock can be held to as high an elevation as economically feasible to minimize cuts into the gypsum rock. To reduce the potential for long-term formation of dissolution cavities from rainwater runoff, the design must minimize the amount of exposed rock in the cut sections after construction.
As the design of the new alignments progresses, additional geotechnical borings should be performed to confirm the competency of subsurface materials immediately beneath the proposed highway alignment.

SUMMARY

In summary, electrical resistivity geophysical surveying along approximately 19,000 feet of US-412, identified approximately 2,300 feet as areas most likely to cause difficulty during and after construction due to the presence of subsurface voids. The design team must minimize the impact of the new roadway to the identified karst formation areas. The design should consider lined ditches to channel stormwater away from the karst formation areas, minimize cuts into known karst formations, and maximize fills and consider rock rip-rap fill at the base of the fills to bridge sinkholes or depressions. Strong consideration should also be given to modifying the horizontal alignment, if possible, to minimize the depth of cut into the gypsum formations.
REFERENCES:


