Subsurface Void Detection in Oklahoma Evaporite Deposits Using Geophysical Methods

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ABSTRACT

Surface sinks, distressed highway sections, voids and evaporite formations with variable weathering have complicated highway redesign in western Oklahoma. More than 46,000 linear feet of Direct Current (DC) Electrical Resistivity (ER) imaging data were collected, using the Dipole-Dipole technique, along Highways US-64 and US-412 in Major County near Woodward, Oklahoma. The main purpose of the survey was to identify and discriminate 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). Zonge Engineering and Research Organization’s ZETA system was evaluated as an effective tool in mapping subsurface geology.

Preliminary geophysical results were furnished to Terracon, Inc. and, in consultation with the Oklahoma Department of Transportation (ODOT), the locations for eighteen confirming borings were selected. Borehole data correlated very well with the resistivity models and allowed for the assignment of resistivity ranges to specific lithologies, this correlation became the basis of all geophysical data interpretation for the duration of the survey.

The results presented here show that DC ER 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 the common issues confronted when making geologic interpretations based on limited and widely varying data from adjacent borings. Two useful generalizations can be drawn about this specific project area: 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 1000’s of feet along US-412 and US-64 are underlain by clay, weathered gypsum and gypsum-clay as confirmed by the borings, and will not likely pose as many issues with regards to required mitigation efforts. In summary, the ER technique, as confirmed by borings, successfully separated the surveyed areas into sections underlain by claystone and weathered gypsum and into sections with potentially karst gypsum formations requiring different mitigation tactics.

INTRODUCTION

Highway-related construction maintenance is often complicated by subsidence, the presence of sinkholes and natural and man-made voids such as dissolution caves and abandoned mine shafts and adds (Sheets, 2004). Mitigation of these issues often involves timely and expensive drilling programs and use of indiscriminant engineering measures.

Zonge Geosciences, Inc., a Division of Zonge Engineering and Research Organization, Inc. (Zonge) conducted extensive geophysical surveys along three sections of highway under subcontract to Terracon, Inc., and under cooperation of the Oklahoma Department of Transportation (ODOT). The survey

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encompassed three independent areas including two sections of US-412 and one section along US-64 in Woodward and Major Counties, Oklahoma. An initial survey covering a total of approximately 20,500 feet of data coverage was completed, and preliminary processing and interpretation was performed. These preliminary results were used to identify confirmation borehole locations for “ground-truthing” of the geophysical data and to identify areas warranting further investigation. Additional data was later collected, resulting in approximately 46,000 linear feet of data coverage.

*Figure 1:* General site location map showing the Oklahoma US-412 sections #1 and #2 where DC ER surveying was performed.

The objective of the geophysical investigation was to map the vertical and lateral extent of the gypsum unit associated with these dissolution features to help ODOT mitigate possible adverse impacts on planned highway expansion projects. The near-surface geology in the vicinity of US-412 and US-64 consists primarily of clays, claystone, sandstone, limestone and evaporate deposits (gypsum). The later is often extremely susceptible to dissolution from the infiltration of storm water and the movement of groundwater. There are numerous small dissolution features that can be seen outcropping on the sides of
the existing highway, and multiple caves, including the well known Alabaster Caves, are located near the existing US-412.

The geophysical method referred to as Direct Current (DC) electrical resistivity (ER) was selected to map subsurface geology and identify the presence of gypsum and potential subsurface dissolution features. This method is commonly used for void detection, as the resistivity contrast between soil/rock and dissolution features is typically very large. The ER surveys along US-412 and US-64 were designed to provide data to depths of about 60 feet below ground surface along the approximate locations of the proposed new highway alignments.

Along the western section of US-412 (referred to here as section #1), the planned highway lanes are approximately 130 feet (40 meters) and 40 feet (13 meters) offset to the north of the existing road. Along the eastern section of US-412 (referred to here as section #2) the planned highway lanes are approximately 105 feet and 45 feet offset to the south of the existing highway (see Figure 1). The actual locations of the ER surveys were determined by accessibility and terrain, and were selected in consultation with Terracon and ODOT personnel. Terracon provided the locations and elevations of the planned highway in Station-Offset-Elevation (SOE) file and hard copy formats. The ER surveys were referenced to survey markings on the existing road, and were measured by compass and chain methods relative to the centerline of the existing road.

The ER surveys along US-64 (referred to here as area #3) were conducted on a single transect located with a 25 foot offset along the south side of the existing road. The objective of the ER survey in this area was to determine if subsurface geologic features were causing observed roadway damage. The results of geophysical surveys in conjunction with geotechnical borings suggest that the road damage is likely due to clay-rich expandable soils, and it is believed there are no dissolution features in this area. The results of this portion of the investigation are not further discussed herein.

PURPOSE AND SCOPE

As acidic rain and groundwater permeates through fractures and between 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. Large systems of caverns are known to exist in the vicinity of US-412, and this cave system traverses beneath US-412 in one known location where people have reported hearing traffic passing overhead.

This paper presents the results from an extensive geophysical investigation conducted for Terracon and ODOT along Oklahoma highways US-412 and US-64. This case study lends itself as an example of the effective application of 2-D DC resistivity for mapping of subsurface geo-electric structures related to lithology and detecting anomalous zones such as highly resistive features caused by the presence of vadose dissolution features and large caverns.

METHODS

The geophysical technique utilized for this project’s electrical resistivity survey is referred to as the Double-dipole, or more commonly, the dipole-dipole technique (Telford et. al., 1976). 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, 1950).
The signal is normally measured, digitized and recorded to the instrument’s internal memory or directly on an external drive or computer. 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. The mechanisms that allow electric current flow include the movement of free electrons through a metallic lattice referred to as electronic conduction, the movement of ions through an aqueous solution referred to as electrolytic conduction, the movement of ions through a solid crystal lattice referred to as solid electrolytic conduction (Yungul, 1996). Displacement current is the last means of transferring charges, however, this phenomenon is only present in high-frequency time-varying situations and does not apply here (Telford, et. al., 1976).

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.

From Ohm’s Law, 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), the method yields the apparent resistivity (ohm-meters) at a certain “point” below the array:

$$\rho_a = k(\Delta V/I)$$

Where $\rho_a$ is the apparent resistivity (ohm-meters), $k$ is the geometry factor (meters) which is equal to $2\pi a$ for this dipole-dipole array configuration, $\Delta V$ is the measured potential drop across M and N electrodes (volts), and $I$ is the measured output current (amps).

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.
Figure 3: Sequence of data collection in a dipole-dipole ER survey, depicting the construction of a pseudo-section: (a) The first measurement and associated apparent resistivity value, (b) the first diagonal completed with the transmitter dipole at its first station, (c) the transmitter dipole advanced to the 7th transmitter location, and receiver dipole collecting additional soundings, and (d) the completed pseudo-section with the two dipoles at the end of the survey line.

As depicted in Figure 3, 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. The processing method employed to resolve final resistivity models is discussed further in the Data Processing section below.

INSTRUMENTATION

The instrumentation used to perform this geophysical survey is the Zonge Electrical Tomography Acquisition (ZETA) system produced by Zonge Engineering and Research Organization (ZERO). The ZETA system consists of 6 primary components: 1) a 24-volt main power supply to the power-booster, 2) the power-booster unit that outputs up to 400 volts to the transmitter, 3) the transmitter unit that outputs current to the multiplexor (MUX), 4) the MUX unit that coordinates the dipole-dipole array geometry over a 30-channel array, 5) the geophysical data processor (GDP) unit that sets transmitter parameters, controls the transmitter and directly records all essential data (transmitter output currents and receiver-dipole potentials) onto an internal hard-drive, and 6) a laptop computer with the ZETA200 program installed and running.

The ZETA200 program allows the user to set all desired parameters, and is used to synchronize and coordinate the GDP, transmitter and the MUX units. ZETA200 also utilizes a user-written schedule file that controls the MUX unit, allowing the user to use any number of arbitrary electrode geometries and perform a complete contact-resistance check for all active channels prior to performing data collection. Figure 4 illustrates the physical configuration of this system.
The GDP allows data to be recorded on all available channels (multiple receiver dipoles) simultaneously, allowing for fast data acquisition of an entire diagonal in the pseudo-section prior to advancing the transmitter dipole and repeating. This allows the operator to quickly obtain full data coverage for a given spread before advancing along the survey line. Overlapping data coverage at the end and beginning of each spread ensures seamless depth coverage along a given survey line with multiple spreads.

For this survey, the transmitted signal was a 0.5 Hz time domain signal (50% duty cycles). This frequency is low enough to perform a DC ER survey while avoiding significant displacement current and SP effects due to polarized electrodes (Yungul, 1996). Eight cycles were stacked and averaged to comprise one measurement. All measurements were repeated at least one additional time to establish repeatability of data. Adverse affects from cultural features were minimized through proper placement of survey lines.

At each station, electrodes consisting of tin-coated copper grounding braids were buried approximately two-inches deep in the soil. Once a spread of 30 electrodes (290 feet per spread) was in place and connected, data were acquired. 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 that were measured using a Trimble RTK GPS, normally with sub-decimeter accuracy.

**DATA QUALITY**

For this survey, the receiver operator made multiple measurements of each data point while monitoring real-time standard-error values displayed on the screen of the receiver. During ZETA data acquisition, multiple waveforms are stacked and averaged to reduce random noise in the data blocks, and 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 standard error of the mean (SEM) and block repeatability for ZETA.

Some cultural features such as roads, signs, pipelines and fencing were encountered during the course of the survey; however, these did not have significant affects on the data quality. One survey line in area #1 required the removal of metal posts and barbed wire fencing by ODOT personnel to avoid undesired current-paths between electrodes from forming through the fence. The dipole-dipole method is most
sensitive to regions directly between the two dipoles; however, there are occasionally strong contrasts in resistivity near, but not directly under the survey line that can affect the measurements.

DATA PROCESSING

Processing for electrical resistivity data acquired using the ZETA system was performed using software developed by Zonge Engineering and Research Organization (ZERO). The flow chart sequence shown in Figure 5 outlines the main steps in reducing and processing the ER data collected for this project. These programs are made available for commercial use and are sold on worldwide basis with Zonge equipment systems. The data are processed through the SHRED program initially to pre-process raw field data, then TDAVG and TS2DIP to computationally model (in 2D) the resistivity data. Two-dimensional plots are generated using either standard (over-the-counter) GEOSOFT tools (for example) or through Zonge’s ZPLOT package.

**Figure 5:** ZETA data processing flow using SHRED, TDAVG, AVG-GDAT, ZPLOT and GEOSOFT Programs

Briefly, 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.

RESULTS

Preliminary results of the modeled data were provided to Terracon/ODOT in order to determine boring locations to assist in the interpretation of the geophysical data. In the preliminary interpretations, an arbitrary color scale was selected for the resistivity sections, as shown in Figures 6 and 7. This color scale was selected to highlight high resistivities (>500 ohm-m) that might be associated with karst features. Based on these results, and in consultation with Terracon/ODOT, 18 borings were completed. The locations and results of these borings are tabulated in Table 1 below, and their locations are also annotated on the final model cross-sections presented in Appendix A.
After the 18 borings were completed, correlations were made between lithology 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 are: 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 geophysical models was complete, the ranges of model resistivities within a given material were plotted, and are presented on Figure 8. 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:** Color scales used for preliminary and final resistivity results and interpretations.

Survey station numbers, offsets from the center of the existing road and proposed highway elevations are annotated on the final figures, horizontal axes indicate station location (feet) and the vertical axes indicate elevation (feet).
Figure 7: Preliminary results presented with an arbitrary color scale and no interpretations for resistivity lines along US412 highway section #1. The figure includes the proposed highway SOE plotted on the figure as a red-dashed line. The figure also includes relevant field observations, confirmed boring locations and proposed boring locations annotated along the top of the sections. The red regions indicate highly resistive areas most likely containing gypsum or karst geology.
Figure 8: Correlation between resistivity ranges and lithologies derived from borings. These correlations were then used in the final interpretation of geophysical data acquired along Highway US-412.
## Table 1: Boring locations along with completion-depth and some data that were used for ground-truthing of resistivity results.

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Purpose</th>
<th>Completion Depth (feet)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-1</td>
<td>54+000 (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 28-30' 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 and 22' bgs, water loss @ 15.6' 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-9</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-10</td>
<td>56+035 (150' North)</td>
<td>Void and Geotech</td>
<td>35</td>
<td>Water loss @ 4.5' bgs</td>
</tr>
<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>
</tr>
<tr>
<td>B-12</td>
<td>55+680 (150' North)</td>
<td>Void and Geotech</td>
<td>50</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' South)</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' South)</td>
<td>Void and Geotech</td>
<td>64</td>
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<td>B-16</td>
<td>2070+050 (150' South)</td>
<td>Void and Geotech</td>
<td>45</td>
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<tr>
<td>B-17</td>
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<td>Void and Geotech</td>
<td>55</td>
<td>Small Voids from about 36-42' bgs</td>
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<tr>
<td>B-18</td>
<td>618+00 (21' North)</td>
<td>Geotech</td>
<td>50</td>
<td></td>
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</tbody>
</table>
DISCUSSION

There is excellent correlation between resistivity distributions on adjacent transects, revealing linear trends of anomalously high resistivity zones. These correlations are interpreted as linear problematic sections of gypsum trending across the existing road and proposed project area. There is also excellent correlation between the modeling results and outcropping caves and other observations noted in the field.

As seen in Table 1, and the final resistivity modeling results presented in Appendix A, the survey has mapped areas with concentrated anomalies, identifying sections of the highway redesign project area where problematic materials may be encountered at depth. The west section of Highway 412 contains the majority of anomalously high resistivity distributions while large expanses along the east section #2 have relatively low resistivity values. There is some overlap in resistivity values for each lithology type discussed here; however, the general distributions of material types have been mapped successfully.

The results presented here show that DC ER offers an accurate and cost-effective approach to mapping lateral and vertical variations in material properties that can be directly associated with lithology. This helps alleviate common geotechnical issues confronted when making geologic interpretations based on limited and widely varying data from adjacent borings.

More specifically, this project has shown that DC ER can be used to map geology that likely contains subsurface voids. The results presented here demonstrate the usefulness of DC resistivity profiling in helping to effectively mitigate and prevent future highway-related issues related to the presence of and formation of new dissolution features and subsurface voids.

ACKNOWLEDGEMENTS

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REFERENCES

Session 6a_A034

Terracon/ODOT
Highway 412 East Section
Station 1500 to 3000 (Line 5 reference)
2D Inversion Model Resistivity (ohm-m)
Figure 6-11
Terracon/ODOT
Highway 412 East Section
Station 7500-End (Line 5 reference)
2D Inversion Model Resistivity (ohm-m)
Figure 6-15

Approximate SOE of New Highway

Cultural Feature

by Zorge Geosciences, Inc.
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Terracon/ODOT
Highway US-64
2D Inversion Model Resistivity (ohm-m)
Figure 6-16

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