United States Department of Agriculture | **Natural Resources Conservation Service** | **5 Radnor Corporate Center, Suite 200 Radnor, PA 19087-4585**

Subject: ENG -- Geophysical Assistance --

Date: 19 March 1996

To: Ronnie L. Clark
State Conservationist
USDA - NRCS
100 USDA Suite 203
Stillwater, Oklahoma 74074-2655

Purpose:

The alluvial materials comprising the embankment materials at PL-534, Site 12 contains gypsiferous materials. Piping-type collapses have formed in the unconsolidated embankment materials. The purpose of this investigation was use electromagnetic induction (EMI) techniques to help characterize the locations and extent of cavities within this earthen structure.

Participants:

Jim Doolittle, Research Soil Scientist, NRCS, Radnor, PA
Glen Miller, State Geologist, NRCS, Stillwater, OK

Activities:

All field activities were completed during the period of 13 to 15 March 1996.

Introduction

Appropriate construction practices can be used to minimize or circumvent the hazards associated with dissolution features. However, the successful application of mitigation measures requires knowledge of the distribution of dissolution features. Traditionally, borehole observations have been used to acquire this information. Borehole observations provide detailed subsurface information. However, this method is relatively expense and information is restricted to the point of observation. Subsurface properties can be highly variable over short distances and the implied lateral assumptions made from borehole data may be poor. Alternative techniques are needed to improve the assessments of these sites.

A wide array of geophysical methods has been used to detect cavities and other dissolution features. These techniques include electrical resistivity, electromagnetic induction, gravity, ground-penetrating radar, magnetic and seismic. Each of these techniques has advantages and disadvantages. No single geophysical method works well in all geologic environments. For cavity detection, each technique has been demonstrated to be feasible and appropriate for locating anomalies under certain conditions. However, under different conditions, they all have failed. No one single method will solve all cavity detection problems. Using multiple geophysical methods, will improve results. Geophysical methods cannot stand alone. Interpretations derived from geophysical methods must be supported with sound understandings of soil and geologic conditions. In addition, results should be verified with ground truth observations.

Electromagnetic induction (EMI) methods were used in this study. Electromagnetic induction techniques use electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted average conductivity measurement for a column of earthen materials to a specific observation depth. Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the (i) volumetric water content, (ii) type and concentration of ions in solution, (iii) temperature and phase of the soil water, and (iv) amount and type of clays in the soil matrix, (McNeill, 1980). The apparent conductivity of soils increases with increases in the exchange capacity, water content, and clay content.

Advantages of EMI methods include speed of operation, flexible observation depths (with commercially available systems from 2.5 to 197 feet), and moderate resolution of subsurface features. Results of EMI surveys are interpretable in the field. This technique can provide in a relatively short time the large number of observations needed for site characterization and assessments. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions and planning further investigations.

This technique has been used to determine depths to bedrock (Palacky and Stephens, 1990; Zalasiewicz et al., 1985) and to locate water-bearing fracture zones in bedrock (McNeill, 1991; Olayinka, 1990). These studies have documented that this noninvasive technique is facile and can be applied over broad areas and soils. Electromagnetic induction techniques have been used in areas of karst (Canace and Dalton, 1984; Pazuniak, 1989; Robinson-Poteet, 1989; Rumbens, 1990). In these studies, interpretations of EMI data enabled the delineation of larger subsurface voids, channels, and zones of higher permeability (such as fractures and karstified areas within carbonate bedrock). Typically, the shape and pattern of the subsurface anomaly have been used to identify the solution feature. I am unaware of any study conducted on earthen embankments in areas of gypsiferous materials.

The EMI survey was designed to help characterize the site, identify areas with anomalous electrical conductivity, suggest possible location(s) of subsurface cavities and/or define the extent of potential seepage. Variations in values of apparent conductivity were presumed to reflect differences in water, clay, and soluble salt contents.

Equipment:

The electromagnetic induction meters were the EM31 and EM34-3, manufactured by Geonics Limited. These meters are portable and require either one or two persons to operate. Principles of operation have been described by McNeill (1980). Each meter provides limited vertical resolution and depth information. For each meter, lateral resolution is approximately equal to the intercoil spacing. The observation depth is dependent upon intercoil spacing, transmission frequency, and coil orientation. Table 1 lists the anticipated observation depths for the two meters with different intercoil spacings and coil orientations. Observation depths can be varied by changing coil orientation, intercoil spacing, and/or frequency.

The EM31 meter has a fixed intercoil spacing of 12 feet. It operates at a frequency of 9.8 kHz. The EM31 meter has effective observation depths of about 9.8 and 19.7 feet in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). The EM34-3 meter consists of two coils and three fixed reference cables with intercoil spacings of about 33, 66, and 131 feet. One of the coils serves as the transmitter, the other as the receiver. In an attempt to balance the desired observation depth (about 35 feet) and optimize the resolution of subsurface features, only the 33 feet (10 m) reference cable was used in this study. With a 33 ft intercoil spacing, the meter operates at a frequency of 6.4 kHz and has observation depths of about 25 and 49 feet in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

TABLE 1
Depth of Measurement
(All measurements are in feet)

Meter	Intercoil Spacing	Depth of Measurement Horizontal	Vertical
EM31	12.1	9.8	19.7
EM34-3	32.8	24.6	49.2
	65.6	49.2	98.4
	131.2	98.4	196.7

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc., was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation. Because of the narrow width of the survey area, disproportionate scales were used in all two-dimensional plots.

In each of the enclosed simulated plots of the study area, colors and filled contour lines have been used. These features have been used to help emphasize spatial patterns. Other than showing trends and patterns (e.g., zones of higher or lower electrical conductivity) in values of apparent conductivity, no significance should be attached to the colors themselves.

Study Area:

The site is located about eight miles southeast of the town of Ft. Cobb, Oklahoma. Figure 1 shows the approximate location of PL-534, Site 12 in Caddo County. The site has a drainage area of about 3,220 acres. The dam has a height of 37 feet and contains 99,398 cubic yards of fill.

The site is located in areas of Cyril fine sandy loam and Gracemont soils (Moffatt, 1973). Cyril soils are members of the coarse-loamy, mixed thermic Cumulic Haplustolls family. Gracemont soils are members of the coarse-loamy, mixed, calcareous, thermic Typic Udifluvent family. These very deep, medium textured soils formed on flood plains in calcareous materials. The underlying alluvial materials consist of stratified silts and sands derived from the Cloud Chief Formation (Barngrover, 1970). These sediments contain high concentrations of gypsum. The alluvial materials are variable in thickness and overlie the Rush Spring Formation.

Before construction of the embankment, numerous potholes were identified in the stream channel (Barngrover, 1970). In these potholes, water was replenished by artesian flow.

Field Procedures:

A survey grid was established across the embankment. The grid interval was 100 feet. At each grid intersection (142), a survey flag was inserted in the ground and served as an observation point. At 140 observation points, the relative elevation of the surface was determined with a level and stadia rod.

The topography of the survey area is shown in Figure 2. The contour interval is two feet. Relief is 40.7 feet. In Figure 2, the centerline of the lateral is along north-south line 150 feet. The approximate locations of the principal spillway tower and six solution holes have also been shown.

The presence of standing water or steep slopes restricted the recording of EMI measurements at some observation points. Measurements were taken with an EM31 and an EM34-3 meter at 138 and 137 grid intersections, respectively. Measurements were taken with meters placed on the ground surface in both the horizontal and vertical dipole orientations.

Discussion:

Background

Electromagnetic inductive methods measure vertical and lateral variations in the apparent electrical conductivity of earthen materials. The apparent electrical conductivity of earthen materials will increase with increasing amounts of soluble salts, clay, and water. The actual values of apparent conductivity are seldom diagnostic, but lateral and vertical variations in these measurements can be used to infer changes in soils and earthen materials. Interpretations of the EMI data are based on the identification of spatial patterns within data sets.

Electromagnetic induction techniques are not suitable for use in all investigations. Generally, the use of EMI techniques has been most successful in areas where subsurface properties are reasonably homogeneous, the effects of one property (e.g. clay, water, or salt content) dominates over the other properties, and variations in EMI response can be related to changes in the dominant property (Cook et al., 1989).

An essential assumption of this investigation is that cavities will appear as anomalies on plots of apparent conductivity measurements. Negative (lower values) anomalies are believed to indicate possible air-filled cavities. These cavities have lower electrical conductivities than the surrounding medium. Positive (higher values) anomalies are believed to indicate possible water- or sediment-filled cavities. These cavities have higher electrical conductivities than the surrounding medium.

The detection of subsurface cavities is extremely challenging. Under favorable conditions, detection is possible, but is often fortuitous. Detection of subsurface anomalies often depends on the number and spacing of observations. The spacing must be comparable to the size of the feature being investigated.

The success of an EMI survey will depend on the size, depth, shape, and spatial distribution of the cavities. Cavities must have a favorable size to depth ratio. Large and/or very shallow cavities are most often detected. Small and deep cavities are often not detected. As a rule, to be detected, the depth to a cavity should be less than 1.5 to 2 times its diameter. Cavities observed at the time of the survey had maximum diameters of less than 12 feet. Accordingly, the maximum depth at which similar cavities can be detected is about 24 feet. Because the embankment is about 37 feet high, to be detected, cavities near the base and along the centerline of this structure must be fairly large (>18 feet).

Because of low signal to noise ratios, cavities are more difficult to detect in highly variable materials. The embankment and the underlying and adjacent earthen materials are stratified and variable in composition. The presence of these contrasting materials made interpretations less straightforward and more ambiguous. Because of their more contrasting electrical conductivity, air-filled cavities are often easier to detect than water or sediment-filled cavities. However, the existence of either air- or sediment-filled cavities was unclear.

Survey Results

The EMI survey was designed to help characterize the site, identify areas with anomalous electrical conductivity, suggest possible location(s) of subsurface cavities, and/or the extent of potential seepage. Variations in values of apparent conductivity were presumed to reflect differences in water, clay, and soluble salt contents.

Basic statistics for the EMI data collected within the study area are displayed in Table 2. In general, values of apparent conductivity appear to increase and then decrease with increasing observation depths. These general trends are believed to reflect alternating strata of dissimilar alluvium, embankment materials, and lithologic layers. Vertical trends in values of apparent conductivity support the enrichment of near-surface layers with soluble salts. For the shallower-sensing EM31 meter, one-half of the observations had values of apparent conductivity between 41 and 58 mS/m in the horizontal (0 to 9.8 feet), and between 50 and 67 mS/m in the vertical (0 to 19.7 feet) dipole orientations. For the deeper-sensing EM34 meter, one-half of the observations had values of apparent conductivity between 40 and 52 mS/m in the horizontal (0 to 24.6 feet), and between 34 and 50 mS/m in the vertical (0 to 49 feet) dipole orientations.

Table 2
Basic Statistics
EMI Survey
Ft Cobb Laterals, Site 12
(All values are in mS/m)

				Quartiles			
Meter	**Orientation**	**Minimum**	**Maximum**	**1st**	**Median**	**3rd**	**Average**
EM31	**Horizontal**	**28.0**	**80.0**	**41.0**	**50.0**	**58.0**	**50.5**
EM31	**Vertical**	**31.0**	**91.0**	**50.0**	**60.0**	**67.0**	**58.3**
EM34-3	**Horizontal**	**30.0**	**70.0**	**40.0**	**45.0**	**52.0**	**46.0**
EM34-3	**Vertical**	**21.0**	**69.0**	**34.0**	**44.0**	**50.0**	**42.6**

These vertical trends support the occurrence of stratified layers of variable compositions. The vertical trends in apparent conductivity also suggest the presence of more conductive layers within the upper 19.7 feet. These relatively shallow layers could have higher electrical conductivity because of higher soluble salt or clay contents. At greater depths, conductivity decreases. This suggests the presence of more resistive materials (i.e., sandier alluvial layers, the Rush Spring Formation) and/or a lower concentration of soluble salts and/or moisture (water could be perched above the Rush Spring Formation).

Figures 3 and 4 are two-dimensional computer simulations of the data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. Figures 5 and 6 are two-dimensional computer simulations of the data collected with the EM34 meter (with a 32.8 ft (10 m) intercoil spacing) in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

Figures 3 and 4 respectively show the spatial distribution (horizontal) of apparent conductivity values within the upper 9.8 feet and the upper 19.7 feet. In these figures, disparate values and spatial patterns are apparent between embankment and toe slope materials. On higher-lying embankment materials (see Figure 2), values of electrical conductivity are relatively low and patterns appear linear. The higher-lying embankment materials are presumed to have lower moisture and soluble salt contents than the lower-lying toe slope materials. The linear patterns are believed to reflect the layering of embankment materials and the progressive decline in moisture with increasing slope positions (terrain effect).

Values of apparent conductivity are higher and more variable along the toe of the embankment. On toe slope areas, patterns are more complex. On the upstream side of the embankment, the impounded water had recently been drained and the soils and earthen materials had high moisture contents. In addition, the former shoreline was believed to be enriched with soluble salts.

In Figures 3 and 4, areas with exceptionally high apparent conductivity values (greater than 60 mS/m) are believed to contain relatively high concentrations of soluble salts. However, this assumption could not be verified at the time of the EMI survey. In other areas of the Midwest, similar values would suggest saline or sodium-affected soils. In areas of saline or sodium-affected soils, the distribution of salts is variable. This variability produces complex spatial patterns on plots of apparent conductivity values. The nodes of higher apparent conductivity values appearing in these figures are believed to indicate the unequal distribution of salts. On the down slope side of the embankment, these patterns suggest zones of more saturated materials and potential seepage.

Figures 5 and 6 represent data collected with the EM34 meter. Data reflect the greater volume and depth of earthen materials profiled. It is assumed that data collected in the vertical dipole orientation (Figure 6) profiled to depths below the maximum thickness of the embankment materials (about 37 feet).

The patterns appearing in figures 5 and 6 are assumed to reflect the thickness of the embankment materials, the composition of the underlying stratified materials, and variations in the concentration of clay, water, and soluble salts within these materials. Compared with toe slope areas, values of apparent conductivity are conspicuously lower on the higher-lying portions of the embankment. This relationship is believed to principally reflect variations in moisture and soluble salt contents between the two areas. Within the upper 24.6 feet, values of apparent conductivity were generally less than 44 mS/m on higher-lying portions of the embankment (see Figure 5). For the same depth interval, values of apparent conductivity were generally greater than 48 mS/m on toe slope areas (see Figure 5).

Along the toe of the embankment, values of apparent conductivity are comparatively high and spatial patterns appear irregular and complex (see figures 5 and 6). In both figures, the toe slope areas appear as relatively broad zones of higher apparent conductivity values. Within these zones, values of apparent conductivity are highly variable over short distances and several nodes are apparent in each figure. Nodes are believed to represent areas enriched with soluble salts and water. These features could reflect preferred channels or pathways of flow. On the downstream side of the embankment, nodes of higher apparent conductivity values are more numerous and conspicuous. These nodes are presumed to represent points of seepage through the embankment or artesian flow.

In both figures 5 and 6, values of apparent conductivity are conspicuously lower on the higher-lying portions of the embankment than on the lower-lying toe slope areas. Within the embankment, values of apparent conductivity decrease with increasing observation depth. On higher-lying portions of the embankment, values of apparent conductivity measured with the shallower-sensing horizontal dipole orientation were generally less than 44 mS/m (see Figure 5). Along the center line of the embankment, values of apparent conductivity measured with the deeper-sensing vertical dipole orientation were commonly less than 32 mS/m (see Figure 6). Values of apparent conductivity measured with the shallower-sensing horizontal dipole orientation were slightly higher along the centerline of the embankment. Therefore, it must be concluded that the centerline of the embankment is underlain by slightly more resistive materials. This suggests the presence of underlying materials that have lower moisture, soluble salts, or clay contents.

Along the centerline (north-south line 150 feet) and on higher-lying portions of the embankment, isolines are linear and appear to parallel the contours. These values are presumed to reflect the spacing and number of observations, composition of the layered embankment materials and variations in soil moisture and soluble salt contents produced by the terrain.

Large voids located within the embankment should produce noticeable anomalies with lower apparent conductivity values. In Figure 6, several areas with anomalously low values (< 28 mS/m) appear along the centerline of the embankment. It is reasonable to assume that these low values reflect areas underlain by relatively dry and/or coarse-textured embankment materials. Another premise is that the bedrock underlies these anomalous areas at relatively shallow depths. Assuming that the observation depth (about 49 feet) is correct, these values could testify to the integrity of the embankment core. No zones of higher apparent conductivity values cross the structure. This observation could be interpreted to suggest that no lateral flow of water or soluble salts crosses the structure (at least to the depth of observation), or that the large volume of material scanned has diluted the resolution of smaller cavities and conduits.

It could also be hypothesized that areas of anomalously low values along the centerline indicate the locations of large subsurface cavities. These cavities would be located within or at the base of the embankment. The general appearance and shape of these anomalies conform with, rather than cross the centerline of the embankment. This could be an artifact caused by the grid spacing. An exception to this arrangement can be observed between east-west lines 700 and 750 (see Figure 6). Here an area with anomalously low values appears to be orientated orthogonal to the centerline of the embankment.

It is equally probable that the observed anomalies along the centerline of the embankment do not represent cavities within the structure. Under this interpretation, it must be presumed, that either the cavities were missed because of the relatively coarse grid spacing (50 feet), were too small to be detected, or were not present.

Figures 7 through 10 have been prepared as alternative presentations of the data collected with the EM34-3 meter in the horizontal and dipole orientations. In each of these figures, the two-dimensional patterns of apparent conductivity values have been overlaid upon a three-dimensional surface net diagram of the topography. For each of the two data sets, two viewpoints are presented; one from upstream (Figures 8 and 10) and one from downstream (figures 7 and 9). These figures will hopefully allow the reviewers a better opportunity to visualize the data.

Results:

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations should be verified by ground-truth observations.

2. Electromagnetic induction methods were used to characterize a dam sites composed of gypsiferous materials. Interpretations were based on the identification of spatial patterns within the data sets. Interpretations were based upon the available information concerning the nature and complexity of soil, geologic, and terrain conditions at the site, and complementary exploratory observations. The ability of EMI

techniques to locate solution features requires a favorable size to depth ratio and a significant contrast in apparent electrical conductivity across the solution features. In addition, detection depends on local ground conditions, presence of interfering cultural features, and the sensitivity and observation depths of a particular meter.

3. The survey produced several recognizable patterns within the structure. These patterns may allow engineers and geologist familiar with the site to render opinions as to the nature and extent of the problem. These patterns can provide the rationale for locating further borehole observation sites.

4. The results of this survey afford several possible interpretations. This is unfortunate. I have provided in this report several possible interpretations for the patterns evident in the enclosed plots. Other interpretations are invited. Patterns and interpretations can be used to help characterize the site and as guides to planning and remedial action. The products of this survey can be used to identify areas with anomalous electrical conductivity, suggest possible location(s) of subsurface cavities, define the extent of potential seepage, and guide and reduce the number of exploratory borehole observations.

It was my pleasure to respond to your request and hopefully to be of assistance to your staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
L. Caldwell, State Conservation Engineer, USDA-NRCS, 100 USDA Suite 203, Stillwater, OK 74074-2655
J. Culver, Soil Scientist, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152,100 Centennial Mall North, Lincoln, NE 68508-3866
S. Holzhey, Soil Scientist, USDA-NRCS, National Soil Survey Center, Federal Building, Room 152, 100 Centennial Mall North, Lincoln, NE 68508-3866
G. Miller, State Geologist, USDA-NRCS, 100 USDA Suite 203, Stillwater, OK 74074-2655

References

Barngrover, D. 1970. Detailed Geologic Investigation of Dam Sites. Ft Cobb Laterals, Site No. 12. USDA-Soil Conservation Service, Stillwater, OK. pp. 12.

Cook, P. G., M. W. Hughes, G. R. Walker, and G. B. Allison. 1989. The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. Journal of Hydrology 107:251-265.

Canace, R. and R. Dalton. 1984. A geological survey's cooperative approach to analyzing and remedying a sinkhole related disaster in an urban environment. pp. 342-348. IN: Proceedings of the First Multidisciplinary Conference on Sinkholes. Orlando, Florida. 15 to 17 October 1984.

Cook, P. G., M. W. Hughes, G. R. Walker, and G. B. Allison. 1989. The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. Journal of Hydrology 107:251-265.

McNeill, J. D. 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Technical Note TN-6. Geonics Limited, Mississauga, Ontario. 15 p.

McNeill, J. D. 1991. Advance in electromagnetic methods for groundwater studies. Geoexplorations 27:65-80.

Moffatt, H. H. 1973. Soil Survey of Caddo County, Oklahoma. USDA-Soil Conservation Service. U. S. Government Printing Office. Washington, D. C. pp. 72.

Olayinka, A. I. 1990. Electromagnetic profiling for groundwater in Precambrian basement complex areas of Nigeria. Nordic Hydrology 21:205-216.

Palacky, G. J. and L. E. Stephens. 1990. Mapping of Quaternary sediments in northeastern Ontario using ground electromagnetic methods. Geophysics 55:1596-1604.

Pazuniak, B. L. 1989. Subsurface investigation response to sinkhole activity at an eastern Pennsylvania site. pp. 263-269. IN: Proceedings of the 3rd Multidisciplinary Conference on Sinkholes. St. Petersburg Beach, Florida. 2 to 4 October 1989.

Robinson-Poteet, D. 1989. Using terrain conductivity to detect subsurface voids and caves in a limestone formation. pp. 271-279. IN: Proceedings of the 3rd Multidisciplinary Conference on Sinkholes. St. Petersburg Beach, Florida. 2 to 4 October 1989.

Rumbens, A. J. 1990. Detection of cavities in karstic terrain: road subsidence - Snowy Mountains Highway near Yarrangobilly, State of new South Wales - Australia. Exploration Geophysics 21:121-24.

Zalasiewicz, J. A., S. J. Mathers, and J. D. Cornwell. 1985. The application of ground conductivity measurements to geological mapping. Q. J. English Geol. London 18:139-148.

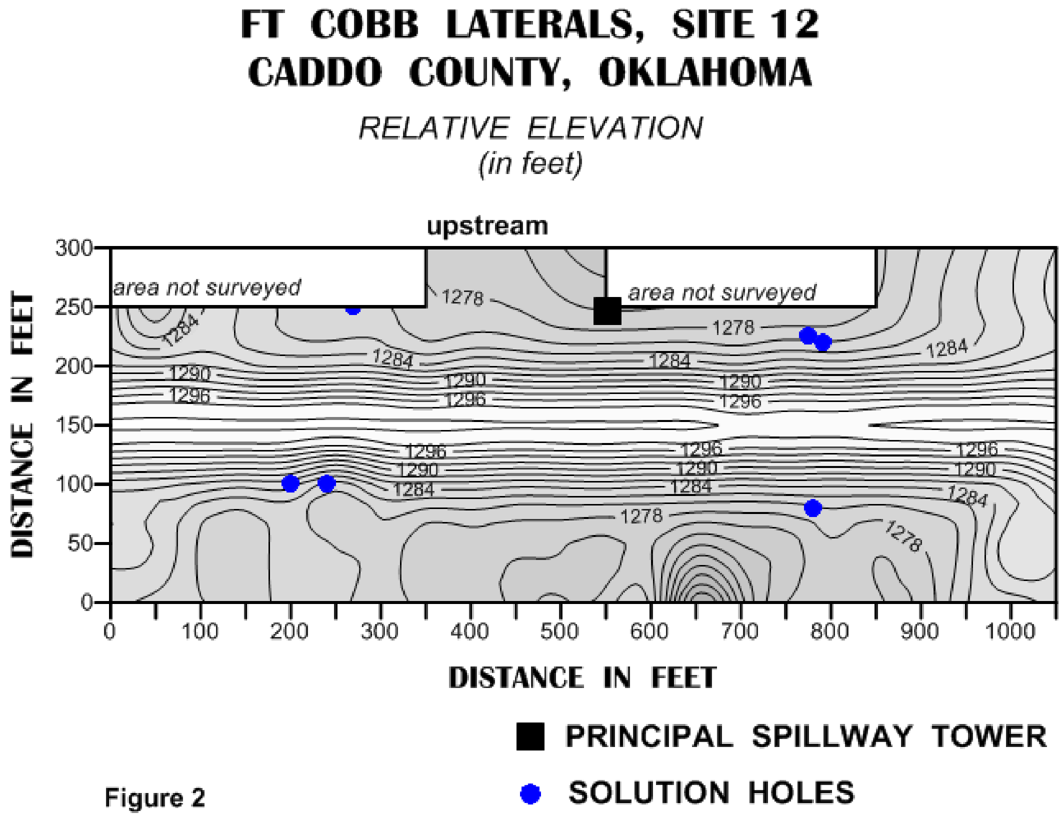

Figure 2

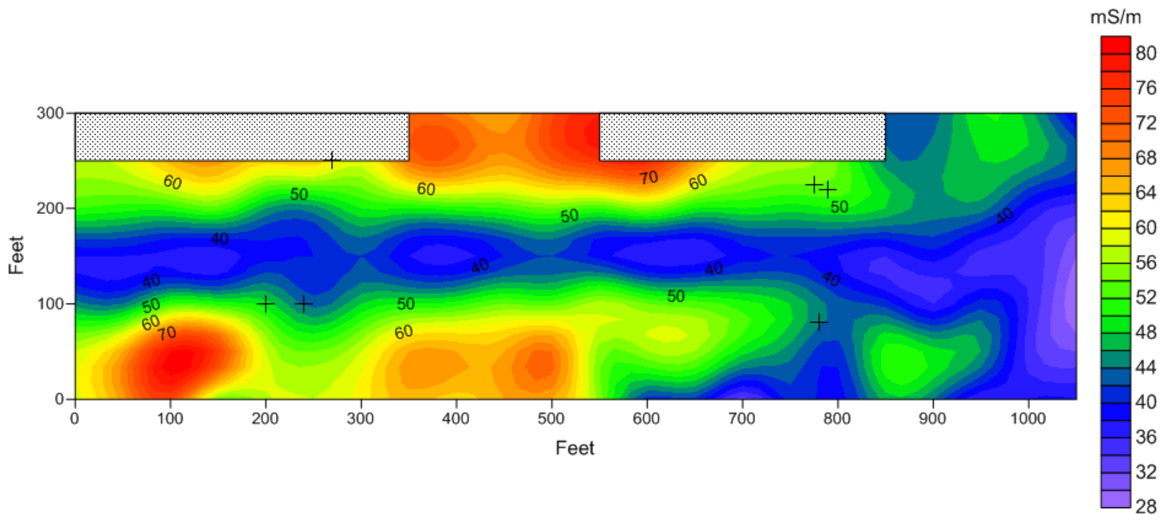

Figure 3

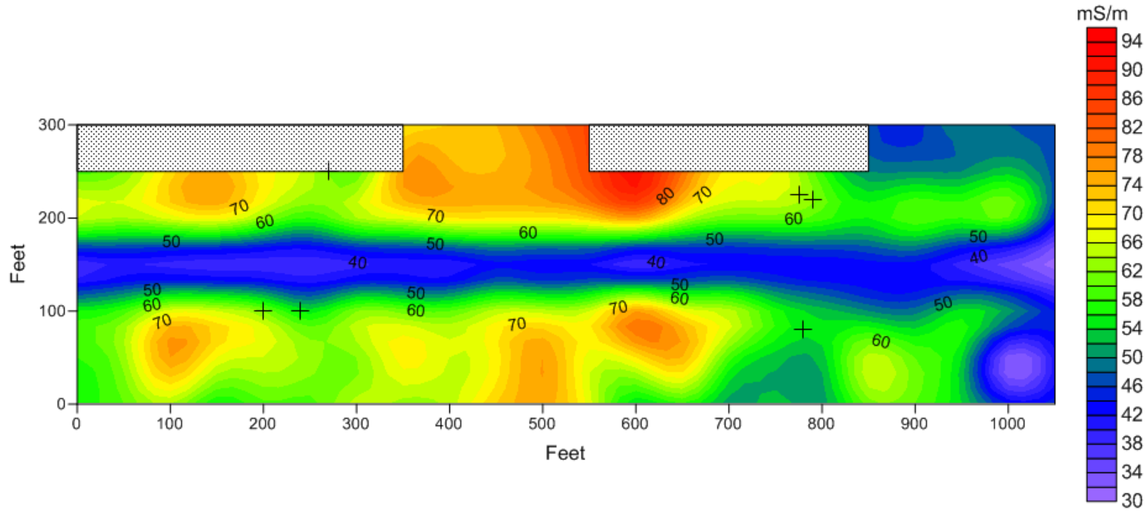

Figure 4

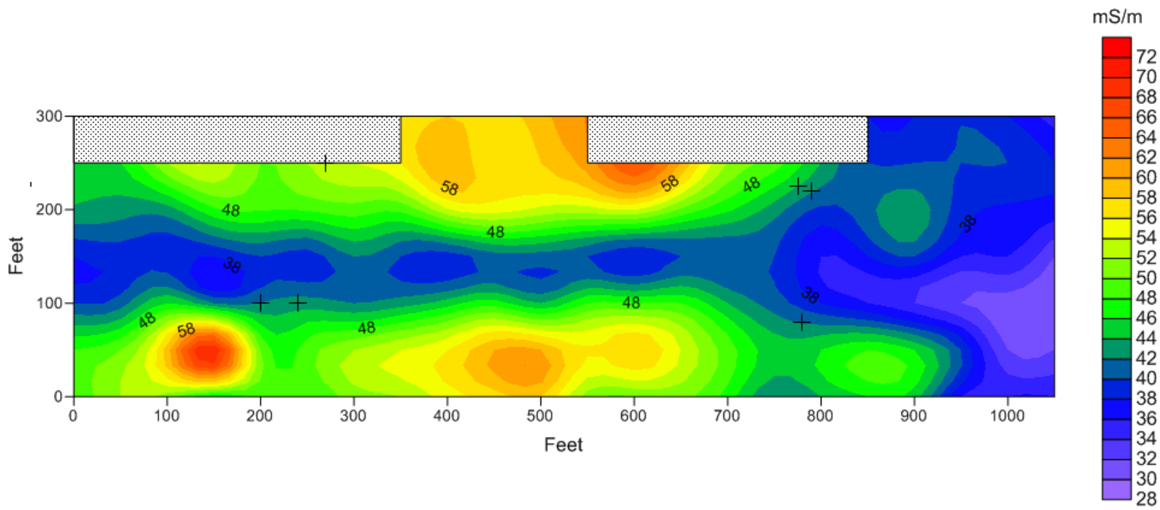

Figure 5

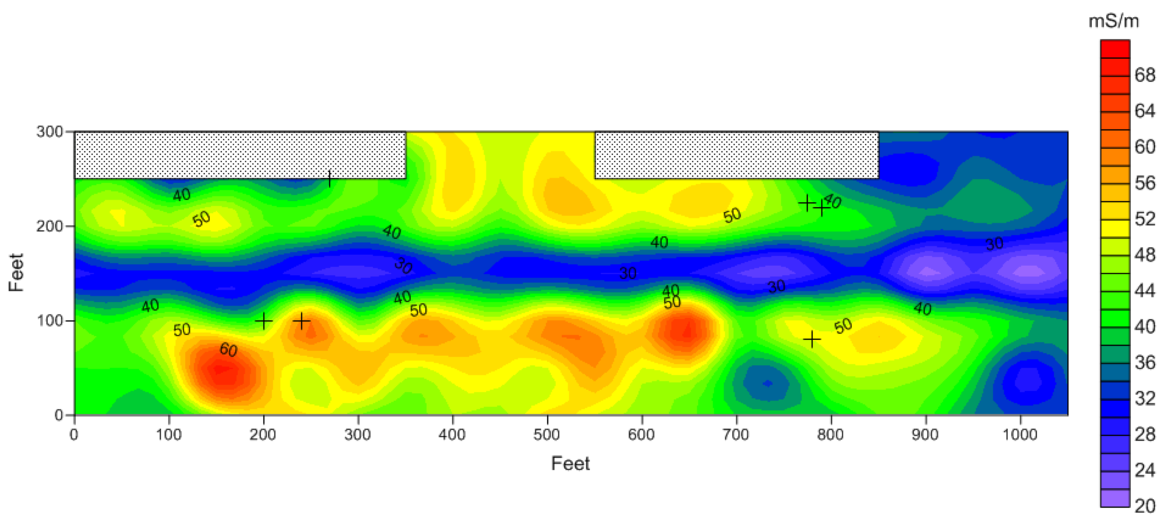

Figure 6

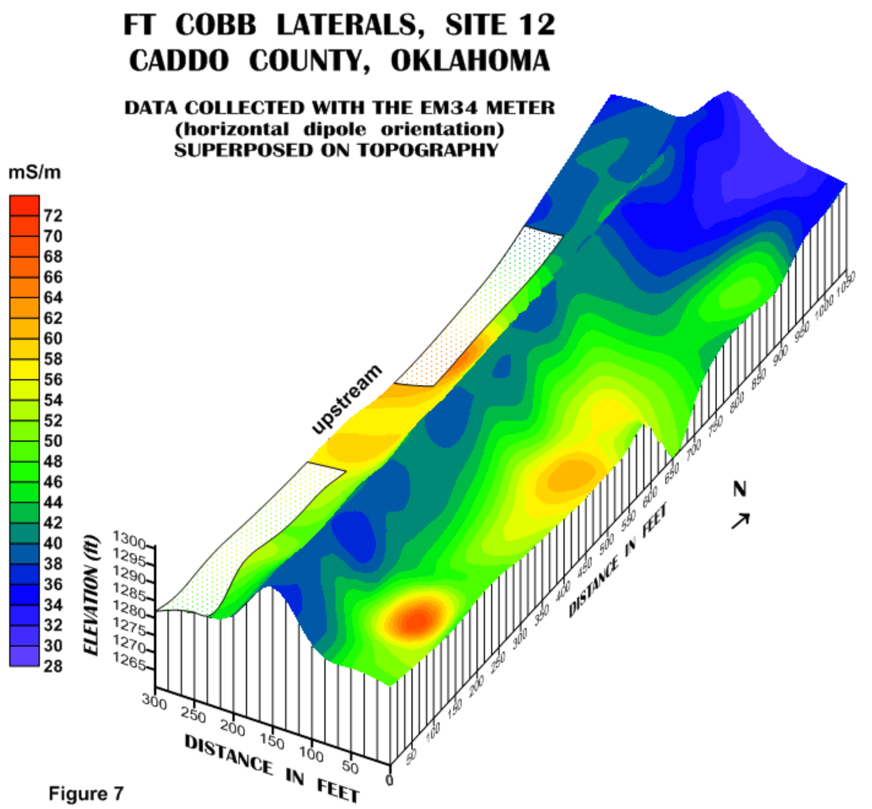

Figure 7

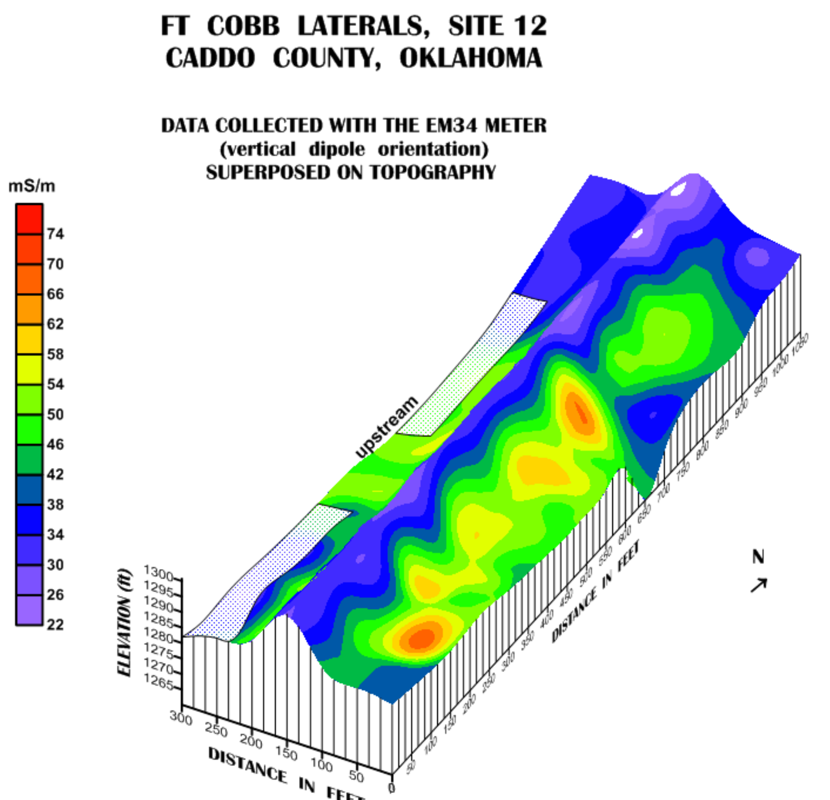

Figure 9

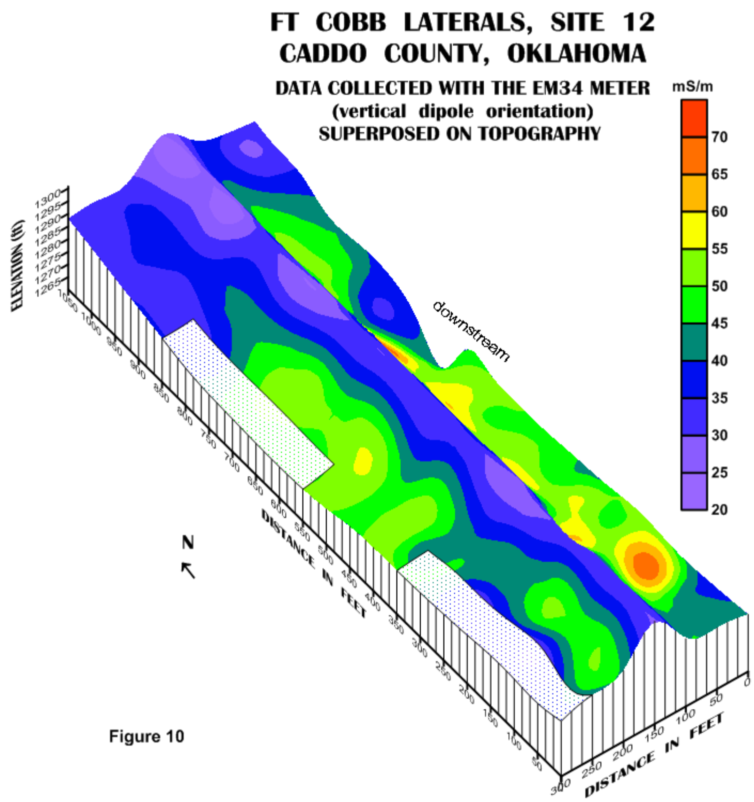
FT COBB LATERALS, SITE 12
CADDO COUNTY, OKLAHOMA
DATA COLLECTED WITH THE EM34 METER
(vertical dipole orientation)
SUPERPOSED ON TOPOGRAPHY
mS/m
70
65
60
55
50
45
40
35
30
25
20
ELEVATION (ft)
downstream
N
DISTANCE IN FEET
DISTANCE IN FEET

Figure 10