EVALUATION OF CAPACITIVELY-COUPLED ELECTRICAL RESISTIVITY FOR LOCATING SOLUTION CAVITIES OVERLAIN BY CLAY-RICH SOILS

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Evaluation of Capacitively-Coupled Electrical Resistivity for Locating Solution Cavities Overlain by Clay-rich Soils

ABSTRACT

Dr. Charles Onasch, Advisor

The introduction of capacitively-coupled resistivity instruments has greatly decreased the amount of time required for the collection of high quality resistivity data. To date, most studies using this equipment have been done in areas with resistive overburden, which enhances the depth of penetration. Much less is known about the performance of this equipment in areas with conductive overburden. The purpose of this study is to test the capacitively-coupled resistivity method for the detection of cavities in areas overlain by clay-rich soils.

Two sites were investigated: Crystal Rock Cave in Erie County, Ohio consists of a sandy clay soil overlying a known cave system; and Dunbridge in Wood County, Ohio, which has a dense clay till overlying a single solution cavity that most likely is a product of oilfield activity. Data were collected with a Geometrics OhmMapper capacitively-coupled resistivity system along traverses at each site and processed using the Geometrics MagMap™ 2000 software. Res2Dinv software was then used to invert the field data and produce resistivity cross sections along the traverses.

Resistivity traverses at the Crystal Rock Cave site were completed with transmitter-receiver separation distances of up to 40 m, which correspond to depths of approximately 12 m. When inverted, the data showed a number of suspected sinkholes and cavities, some of which correspond to known cave locations. Traverses at the Dunbridge site were completed with
transmitter-receiver separation distances of only 15 m, which limited the depth of penetration to approximately 4 m. Although the survey yielded apparent resistivity values consistent with clay-rich soils, it failed to unequivocally locate the solution cavity.

This study has shown that while capacitively-coupled resistivity systems have the potential to perform well in light clay soils or resistive overburden, this method would not be the preferred method of data collection in areas with thick, clay-rich overburden. Although this method was effective in finding buried cavities at the Crystal Rock Cave Site, it failed to provide an unambiguous interpretation of the subsurface at the Dunbridge location.
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INTRODUCTION

Electrical resistivity methods are widely used in the identification of solution cavities in karst terranes. Locating these structures with other methods, such as seismic reflection or gravity, is often difficult because the structure is covered by a thick overburden of soil or sediment (Kruse et al., 2006). As populations grow and development in karst regions becomes a necessity, so does the need for a quick, inexpensive method to locate the hazards associated with karst terranes. Traditionally, random geo-probing or coring has been the only way of identifying soil thickness or depth to bedrock, which is important to know when considering development of the land surface in these areas. These methods are not only expensive, but can be inaccurate, yielding an incomplete picture of the subsurface (Zhou et al., 2002). Identifying solution cavities is important, especially when considering the effects on buildings and infrastructure, as well as the potential impact on valuable groundwater resources. Resistivity surveys using towed arrays have shown excellent results in areas with sandy or gravelly overburden, showing distinct lithologic variations with precision and clarity (Baines et al., 2002). In karst-dominated areas, traditional resistivity imaging (i.e., fixed electrode arrays) has also shown excellent results in identifying covered karst cavities because of distinct variations in resistivity between overlying clay, carbonate bedrock, and water/air-filled cavities (Zhou, 2000).

Although traditional fixed-probe resistivity surveys have yielded excellent results in clay soils, towed arrays, which use principles such as electromagnetic induction to produce a current in the ground, have not been thoroughly tested in these soils. Clay soils present multiple problems for resistivity surveys, which are associated with their electrical properties. Clay soils often contain higher levels of water than other soils, lowering their resistivities. When conducting resistivity surveys it is often difficult to accurately distinguish lateral changes in
materials from lateral variations in water content. Since clay soils have low resistivities (Burger, 1992), they will limit the depth of penetration of electrical current thereby limiting the depth that subsurface information can be gathered (Fig. 1). Therefore, in areas with thick, water-saturated clay deposits, the effectiveness of resistivity surveys is considerably reduced. Towed arrays have showed excellent results in other terranes (Garmon and Purcell, 2006), suggesting that similar results could be obtained in thick clay soils.

![Figure 1. Current flow lines in conductive clay overlying bedrock. Current flow lines are preferentially located in the conductive clay and do not penetrate the bedrock. Therefore, no information about bedrock is obtained.](image)

**Objectives**

The objective of this study is to evaluate the effectiveness of capacitively-coupled towed arrays to identify cavities in carbonate bedrock overlain by clay-rich soils.

**Background**

**Karst Solution Features**

In areas underlain by carbonate bedrock, dissolution of the bedrock by ground water can have disastrous effects on development in these areas. Ground water is typically slightly acidic
and reacts chemically with highly soluble carbonate bedrock. The dissolution of these rocks forms many landforms, some of the more familiar being caves and sinkholes (Easterbrook, 1993).

The formation of these landforms often requires large amounts of water with high levels of dissolved CO$_2$, and forms readily in areas with tropical climates and high amounts of rainfall. In these environments, the dissolution process takes place more rapidly as vegetation facilitates the development of fractures and conduits, and microbiotic production of CO$_2$ allows for greater partial pressures of CO$_2$ in tropical waters. The combination of these processes often produces well developed karst features (Easterbrook, 1993).

The formation of the acidic solutions responsible for the formation of karst features is a multiple step process. The process begins with the reaction of ground water or rainwater and CO$_2$ to form H$_2$CO$_3$, or carbonic acid (Mylorie and White, 1992). The amount of CO$_2$ dissolved in the water depends primarily on the partial pressure of CO$_2$ in the atmosphere, the pore space of the rock, and the temperature of the rock. Increasing the partial pressure of CO$_2$ in the air and/or decreasing the temperature of the water will allow for greater amounts of dissolved CO$_2$, therefore allowing for a greater amount of dissolution to occur. The addition of biogenic CO$_2$ to water, such as the dissolved CO$_2$ found in soil water as a result of the decomposition of organic material, also supplies high levels of dissolved CO$_2$ to the dissolution process (Easterbrook, 1993; Mylorie and White, 1992).

The carbonic acid formed dissociates readily into its ionic state, which is represented by the equation, $\text{CO}_2 \text{(dissolved)} + \text{H}_2\text{O} \leftrightarrow \text{H}^+ + \text{HCO}_3^-$. Following the dissociation of carbonic acid, calcite then dissociates by the process $\text{CaCO}_3 \leftrightarrow \text{Ca}^{2+} + \text{CO}_3^{2-}$. Next, the hydrogen from the dissociation of the carbonic acid combines with the carbonate ion, forming another
bicarbonate ion, represented by the following equation: \( \text{CO}_3^{2-} + \text{H}^+ = \text{HCO}_3^- \). During this process, the \( \text{Ca}^{2+} \) ion is released from the calcite into the water. In nature, dissolution and precipitation of \( \text{CaCO}_3 \) occur simultaneously. The bicarbonate ions from the dissolution of calcium carbonate and the dissolving of carbon dioxide in water create disequilibrium between the partial pressures of \( \text{CO}_2 \) in the air and water causing more \( \text{CO}_2 \) to dissolve in water, driving more solution of calcite (Easterbrook, 1993; Ford et al., 1988).

Of primary concern to this study is the presence and formation of caves and solution cavities. Their formation is often related to the location of the water table, as dissolution of the surrounding bedrock is accomplished by the acidic waters mentioned above. Caves and solution cavities often begin to form in the vadose zone, or the area between the surface and the water table. Here, water moves solely under the influence of gravity, migrating through the surrounding bedrock enlarging fractures by dissolution. Cave passages developed in the vadose zone tend to be high, narrow passages called “vadose canyons” (Mylorie and White, 1992; Ford et al., 1988). Caves that form in the vadose zone are often complex networks of vadose canyons and domepits, which are abrupt cylindrical shafts formed by downward flowing water.

When water moves through the vadose zone, it eventually reaches the water table, entering the phreatic zone. Dissolution in this zone occurs along joints and bedding planes. Moving under hydrostatic pressure, water in the phreatic zone effectively dissolves channels, tubes and passages as it migrates through the bedrock. These channels can resemble a large underground river, consisting of a main channel, with smaller tributaries, much like a surface stream (Mylorie and White, 1992).

Caves and solution cavities can also form due to multiple stages of vadose and phreatic development. In these situations, the water table will rise or fall for long periods of time,
allowing for features to develop into unique structures. For instance, a cave system that becomes submerged by the water table may retain many of the features found in vadose zone caves, but also contain multiple passages associated with joints and bedding planes (Ford et al., 1988).

Another example of a multi-stage cavity would be one where the water table drops, exposing cavities that were once submerged to the open air environment found in vadose systems. When a water table drops, usually there is a restructuring of the conduit system which will lead to an advanced network of passages, and multi-level systems. Cavities that are formed in this process are also exposed to new stresses as water is removed from the cavities. Here you will also find collapse structures as roofs and passages collapse because of the removal of structural support from the pressure of the water contained in the cavity (Ford et al., 1988).

**Oil Field Karst**

Dissolution of carbonate to form cavities is a process that can occur regardless of human interaction. While the majority of carbonate dissolution in the subsurface occurs by groundwater, hydrocarbons can accomplish the same result. Oil and gas reserves trapped in carbonate paleokarst reservoirs, termed ‘Oil field karst’ account for approximately 80% of the producing fields in North America (Loucks, 1999). For the purposes of this study, the formation of secondary porosity in these units and their effects on reservoir permeability and porosity is a primary concern. Often found in dolomite, carbonate reservoirs have abundant secondary porosity, making them ideal reservoir rocks (Sun, 1995).

According to Hill (1990), it is possible to initiate the dissolution of carbonate rocks by hydrosulfuric acid with the addition of migrating hydrocarbons. When the newly mobilized hydrocarbons interact with dissolved sulfide ions in water, $\text{H}_2\text{S}$ is formed. As these fluids
continue to mix with oxygen at the water table, hydrosulfuric acid is generated, creating the hypogenic fluids necessary to dissolve the surrounding carbonate bedrock (Hill, 1990; Palmer, 1991). It is believed that the cavity that formed at the Dunbridge site in May of 2007 also formed in this manner, as it is located in an identified oilfield.

Although the dissolution by hypogenic fluids is a different process from that of carbonic dissolution, the cavities and karst features created by this process pose the same threats and issues to groundwater and engineering concerns as the features associated with carbonic dissolution. Identification of these structures in previously drilled fields is an important characteristic to identify when construction or groundwater use is being considered.

**Electrical Resistivity Methods**

Electrical resistivity offers two important advantages for exploring the subsurface compared to other geophysical techniques: it is the least expensive and does not require specialty training to operate the instrument or interpret the data (Sree Devi et al., 2001). Electrical resistivity imaging (ERI) is a tool that applies direct current or low-frequency alternating current to the ground while measuring the potential difference between two points (Fig. 2). Variations in the resistance to current flow cause distinctive variations in the potential difference measurements, which provide information about the subsurface materials and structure.
Traditionally, ERI is done using a series of electrodes positioned in one of several standard configurations (Burger, 1992). The three main configurations are the Wenner, Schlumberger, and dipole-dipole arrays (Fig. 3). Each of these configurations has advantages and disadvantages. The Wenner configuration places each of the electrodes at an even interval $a$, with the current electrodes positioned at the ends, and potential electrodes in the middle (Fig. 3). Using the constant spacing of $a$, the configuration requires that all electrodes must be moved for reading, which requires more field time than the other configurations. This configuration places less demand on instrument sensitivity for larger potential electrode spacings. The Schlumberger configuration, which is used extensively in groundwater investigations in both alluvial and hard rock settings (Yadav et al., 1997), again places the current electrodes to the outside at a distance of $L$, but places the potential electrodes close together with a distance of $MN$ (Fig. 3). The spacings for this configuration are selected to maintain the relationship of $2L > 5MN$ (Burger, 1992). This method requires a large open space along a transect line, which increases the
coverage time, manpower, and effective cost, and is operationally inconvenient and uneconomical for investigations in populated regions (Yadav et al., 1997). In the dipole-dipole configuration, the potential and current electrodes function independently of one another. Each pair is positioned close together with a significant distance between the sets (Fig. 3). This configuration makes it easier to put a large distance between the potential and current electrodes providing a larger current penetration, which allows for deeper investigations, (Burger 1992).

Electrical Resistivity Tomography or Imaging (ERI) is a relatively new technique compared to traditional resistivity techniques, which have been used for approximately 100 years. ERI is best described as a modern extension of traditional techniques, using computers and sophisticated modeling programs to produce 2D images of subsurface resistivity values.

Advancements in electrical resistivity imaging and resistivity techniques have allowed for the rapid production of high-resolution images of the shallow subsurface under many field
conditions. ERI works well in sand and gravel because it measures the resistance of the material to electrical conduction rather than the reflectance of electromagnetic waves (Smith and Sjogren, 2006). Also, sand and gravel have high resistivities, which allows for significant depth of penetration of current flow lines.

Capacitively-coupled resistivity (CCR) is a relatively new resistivity method that uses a transmitter and receiver, arranged in a dipole-dipole configuration (Fig. 4), to produce and measure electrical currents in the ground. A low frequency (16 Hz) alternating current emitted by the transmitter causes current to flow in the ground through electromagnetic inductive coupling, thereby eliminating the need for electrodes. Without the need for electrodes and cables, the CCR method dramatically reduces the amount of time and personnel needed to collect data. The transmitter and receiver assembly is designed to be towed behind a person or an all-terrain vehicle (ATV) (Geometrics, 2007)

Figure 4. Example of OhmMapper CCR geometry, modified from Geometrics (2007).
MATERIALS AND METHODS

Study Area

In order to successfully test the capabilities of CCR towed arrays in areas with clay-rich overburden, two site locations with different geologic settings and histories were selected. Both locations are in northwest Ohio, respectively in Erie and Wood Counties. Both sites have been exposed to similar periods of weathering, erosion, and deposition and are underlain by gently dipping Paleozoic sedimentary rocks. They differ primarily in the thickness and nature of the soils overlying the bedrock (Coogan, 1996; Stuart et al., 1991) and the origin of solution features.

Crystal Rock Cave Site

Crystal Rock Cave is located approximately 3 km east of White’s Landing, Erie County, Ohio just off of Wahl Road (Fig. 5). Underlain by the Silurian Salina Group, this site is a bedrock knob containing multiple exposed cave systems. Composed of a finely crystalline, brown dolostone associated locally with gypsum, shale, or anhydrite, the Salina Group also intertounges with the Tymochtee and Greenfield Dolomites and thins to the south (Shaffer, 1951; Slucher et al., 2006). Multiple authors (White, 1926; Shaffer, 1951; Verber and Stansbery, 1953; Sparling, 1970) have identified the dolomite as being the Put-in-Bay dolomite, which is part of the Bass Island Dolomite of the Salina Group. Caves at this location are described by White (1926) and Verber and Stansbery (1953) as being of the Put-in-Bay type: the cave’s roof and floor were at one time in contact with one another. The formation for these caves indicates that the anhydrite in the underlying Tymochtee Dolomite hydrated into gypsum. The expansion of the anhydrite caused the overlying Put-in-Bay dolomite to bend upwards at angles locally
reaching 30-60 degrees. Removal of the soluble gypsum allowed the floor to collapse leaving the crescent shaped cavities found here. According to White (1926), Crystal Rock Cave is approximately 7 m long and 3.4 m wide, with roof levels of 1.5-2 m high. The cave has two levels; the lower has a pool of water, which is always present. Transects 7 and 8 at this location were positioned near the cave location. Transect 7 is to the east of the known cave location, and Transect 8 overlies the location just north of the cave entrance. The general topography surrounding the bedrock knob is best described as being slightly undulating and slopes gently northwards towards Lake Erie (Sparling, 1970).

Figure 5. Location of the Crystal Rock Cave site in northwest Ohio. Site is outlined in yellow. Lake Erie is visible to the northeast of the site location. Inset maps show location of site within Erie County and Ohio.
**Dunbridge Site**

Located in Wood County, this site is in a farm field approximately 1.6 km north of the town of Dunbridge (Fig. 6). It is located in the Dowling oil field and is underlain by the Silurian Lockport Dolomite. Topographically, this site has little to no relief. The Lockport Dolomite is a finely to coarsely crystalline, white to grey, fossiliferous, and vuggy, with medium to massive beds (Slucher et al., 2006).

In May of 2006, a cavity collapsed at this location, raising the concern of the landowner. The collapsed area consisted of a steep-sided, circular hole in the glacial till 3 m deep and approximately 1.5 m in diameter (Fig. 7). At the base of the till, the cavity opened into a circular cavity in the bedrock 5 m across and 4 m high, with a cone of debris approximately 1 m high located in the center of the floor. Just above the opening, the presence of rough cut 2x4 lumber (Fig. 7) indicated the possibility that this cavity was open previously and subsequently filled by a previous land owner. It is unclear how far the cavity extends beneath the cone of debris. The initial investigation of the site noted the presence of oil residue on the walls of the bedrock cavity (Fig. 8) and also on the ground surface for a distance of approximately 3 m around the opening, indicating a surface discharge of oil-bearing groundwater following the collapse. It is believed that re-pressurization of an abandoned oil well caused the geyser-type discharge seen on the surface. Shortly after the feature formed, the landowner filled it in so that farming could resume.
Figure 6. Location of the Dunbridge site. Site is outlined in yellow. On the county inset, Interstate 75 is identified in brown, S. Dunbridge road is red. Inset maps show location of site within Wood County and Ohio.
Figure 7. Photograph of upper portion of cavity at Dunbridge site showing 2x4 (arrow) in bottom of cavity. Diameter of opening at ground level is 1.5 m.

Figure 8. Roof of cavity in bedrock showing the presence of oil residue. Width of photo is approximately 2 m.
Methods

Electrical Resistivity

To complete the study of the Crystal Rock Cave and the Dunbridge sites, a Geometrics OhmMapper Capacitively-Coupled Resistivity system was used in conjunction with a Trimble ProXR GPS receiver to collect resistivity and location data, respectively. CCR data were gathered along multiple transects at each site; with transect locations that enabled collection of the most complete data set possible for each site. Prior to collection of data, a ‘walk off’ test was performed to verify the correct functioning of the equipment and to get a general sense of the maximum transmitter-receiver separation distances possible. Multiple receiver-transmitter separations ranging from 2.5 to 40 m were used along each transect in order to vary the depth of penetration, which is approximately equal to ½ the separation distance (Burger, 1992).

The data were downloaded and processed using the Geometrics MagMap™ 2000 software. Data processing consisted of using the auto de-spike feature, as well as removal of erroneous data points or transects as noted by the operator in the field. Once processed, contoured cross sections of apparent resistivity (pseudosections) were produced from all the separation distances using Res2Dinv software.

Topography data were added to Transect 7 (see Figure 16) to accurately portray the variations in elevation associated with that particular transect. To add topography data, GPS readings were taken every 10 m along the profile. These data were transferred to a spreadsheet, where the points could be sorted and then added to the data file using the data editor screen (text editor) in Res2Dinv. Specific details on file format and structure can be found in the Res2Dinv manual. Topography was only applied to Transect 7 because the other transects had little to no variation in elevation.
Using Res2Dinv, each transect was checked for data errors and the first electrode was reset to start at zero. In order to obtain the best model possible, each dataset was inverted using model refinement, finite-difference modeling, and the standard Gauss-Newton inversion method. For a more complete review on the data processing and modeling refer to appendix (A).

In order to accurately describe the resistivity variations at the Dunbridge site, it was necessary to create a series of contour maps for each separation distance recorded at the site. These contour maps were created by extracting the specific separation data (i.e. 2.5 m, 5 m etc.) for each transect. Next, these data were combined in a spreadsheet and imported into a contouring program (Golden Software Surfer) where contours of each separation distance were created. Contour maps were only created for the Dunbridge site.

**Errors**

Multiple sources of errors were identified when completing the collection of data at each location. These sources included data noise, speed errors, and data corrections. Where the variation in apparent resistivity is small (<1000 ohm-m), subtle variations in materials and/or water content will make the data appear noisy thereby making interpretation more difficult. This proved to be a problem in the Dunbridge site.

Speed errors occurred when the speed at which the array was moved along the traverse varied between data marker points. This is important because the Ohmmapper system establishes distance based on the number of data points collected in between the 10 m segments flagged in the grid. If the speed is increased or decreased between the segments, the computer will place the associated resistivities at incorrect locations based on the number of data points it takes between segments. This source of error, while detrimental to the overall effect of the
system, is identified to have a maximum offset range of no more than 2 m. This may have been a problem for some of the traverses at the Dunbridge site where an ATV was used to tow the array. At the Crystal Rock Cave site, all data were collected with the operator towing the array, which results in a much more consistent speed.

As outlined previously, data were collected and corrected for missing field points using the Magmap2000 software. These data corrections were necessary to complete data that either through operator error or equipment failure had errors which created problems with the structure of the data. Points (marks showing 10 m segment locations) were inserted or deleted into the grid structure based on observations during the collection of the data. Points added to the structure could cause errors if not placed in the correct location, because the Ohmmapper system establishes distances based on the number of readings between these points.
RESULTS

Crystal Rock Cave Site

Data collection at the Crystal Rock Cave Site in Erie County, Ohio consisted of 8 transects of at least 60 m (Fig. 9). Separations for this site were obtained to a maximum of 40 m with each transect following the pattern of 2.5, 5, 10, 15, 20, 25, 30, 40 m, respectively. Transects 1-6, 8 are presented without topography, as relief on these transects is minimal. Transect 7 has topography applied to the model in order to present a more realistic image. Root-mean-squared (RMS) error values are presented with all transects indicating the percentage of error between the measured data and the calculated data based on the inversion done with the Res2Dinv software.
Figure 9. Transect location map for Crystal Rock Cave Site. Crystal Rock Cave is identified by the red dot; Winkel Cave is identified by the yellow dot.
Transect 1 shows resistivity values from approximately 49 to 49377 ohm-m with lows present across the middle of the profile. Beneath the lows there is a resistivity high that occurs between approximately 100 to 160 m. Profile depth is approximately 11.5 m. This model, using the standard inversion technique, has an RMS error value of 13.6% after 5 iterations.

![Figure 10](image_url)

Figure 10. Contoured resistivity cross section (top) and interpretation (below) along Transect 1. See Figure 9 for location of transect.

Transect 2 shows resistivity values ranging from 50 to 15000 ohm-m, the largest of these variations occurring across the center of the profile from 1.25 m to 10 m depth. Total depth reached for this model is approximately 12 m. After 5 iterations, the RMS error value for Transect 2 is 15.8%. Resistivity highs occur at 50, 80, 100, and 140 m respectively, with varying lows occurring between these areas.
Figure 11. Contoured resistivity cross section (top) and interpretation (below) along Transect 2. See Figure 9 for location of transect.

Transect 3 shows resistivity variations from 13 ohm-m to greater than 7000 ohm-m. Areas of higher resistivity occur from 1.25 m depth across the entire profile. Areas of lower resistivity surround these areas of higher resistivity, with the lowest values occurring in the NE end of the profile. Total depth reached by Transect 3 is approximately 9 m; with an overall transect length of 150 m and an RMS error of 14.0% after 5 iterations.

Figure 12. Contoured resistivity cross section (top) and interpretation (below) along Transect 3. See Figure 9 for location of transect.

Resistivity differences occurring in Transect 4 range from 16 to 10000 ohm-m with the largest values occurring at depths of 6.25 m. Profile depth reaches 11 m, with moderate to high
resistivities occurring from 25 m to 130 m, and again from 150 m to 210 m. Resistivity lows occur irregularly throughout the profile, with a large area of lows from 130 to 150 m. After 4 iterations the final profile of Transect 4 has an RMS error value of 17.8%.

Transect 5 displays changes in resistivity from 7 to approximately 2700 ohm-m. Resistivity highs occur across almost the entire SW end of the profile, reaching depths of up to 9 m, with resistivity lows overlying highs to the NE of the profile. Transect 5 has an RMS error of 13.3% after 5 iterations.

Figure 13. Contoured resistivity cross section (top) and interpretation (below) along Transect 4. See Figure 9 for location of transect.

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Figure 14 Contoured resistivity cross section (top) and interpretation (below) along Transect 5. See Figure 9 for location of transect.
The longest transect recorded at the Crystal Rock Cave Site 270 m, Transect 6, has resistivity ranges are from 15 to 6000 ohm-m, with resistivity highs throughout the transect with lows occurring at the bottom of the profile at the NE end. The profile reaches a maximum depth of 11.3 m and after 4 iterations the model RMS error value is 12.8%.

Figure 15. Contoured resistivity cross section (top) and interpretation (below) along Transect 6. See Figure 9 for location of transect.

Also covering a distance of 270 m, Transect 7 resistivity values range from 30 to 14834 ohm-m with the highest values occurring on the NW end of the profile. Starting from 20 m, higher resistivity values occur at approximately 2 m from the surface and continue along this trend until about 140 m. Here a large band of higher resistivity values can be seen. From 245 m to the end of the profile, the general nature of resistivity alternates between highs and lows. After 5 iterations, the RMS error value for Transect 7 is 8.1%.
Figure 16. Contoured resistivity cross section (top) and interpretation (below) along Transect 7. See Figure 9 for location of transect. Topography was added to this transect to more accurately portray the subsurface anomalies. Elevations were used here because of the greater amount of relief compared to the other transects. The vertical scale on this transect is measured in elevations rather than a standard zero scale to measure topography changes rather than depth.

Transect 8 shows an area of resistivity lows to the SE, but crosses into higher resistivity values in the NW. Alternating higher and lower resistivities best describe NW side of this transect. Resistivity values range from 513 to 12,921 ohm-m and the profile reaches a depth of 3.13 m. The RMS error value after 5 iterations is 3.0%. Depth for Transect 8 is reduced because only the 2.5, 5, and 10 m separations were used due to space issues.
Dunbridge Site

Transects completed at the Dunbridge site used separations of 2.5, 5, 10, and 15 m. Each transect was spaced 5 m from the previous one, forming a grid that covered 260 m per transect (see Figure 18). Maximum depth associated with these transects is 5 m. The location of the filled cavity was noted at 100 m from the start of the 3rd transect (#11 on Figure 18).
Figure 18. Transect location map with transects represented by the number on top of the colored lines. The red dot is the approximate location of the cavity (Figs. 7, 8), identified on Transect 11.

Transect 9 shows major resistivity variations throughout the profile, especially near the surface. Resistivity values range from 1 to 5000 ohm-m. Resistivity highs mainly occur at depths of at least 3 m, but there are highs located at 60 and 200 m at the immediate surface. After 5 iterations the RMS error value is 14.7%.
Figure 19. Contoured resistivity cross section (top) and interpretation (below) along Transect 9. See Figure 18 for location of transect.

Transect 10 model resistivity values range from 1 to 9000 ohm-m with high levels of variation throughout the profile. Resistivity highs occur mainly at the base of the profile, with exceptions at 100 and 120 m. This profile shows lowest values mainly across the middle of the profile at depths of 2.0 – 3.50 m. The RMS value after 5 iterations is 13.6%.

Figure 20. Contoured resistivity cross section (top) and interpretation (below) along Transect 10. See Figure 18 for location of transect.

Transect 11 model has significantly smaller resistivity ranges (0.5 to 511 ohm-m) than other transects. Unlike previous transects at the Dunbridge site higher resistivity values are located primarily within the first half a meter. There is also an area of high resistivity located at a depth of 1.50 – 5 m, from approximately 10 – 40 m. Resistivities along this transect have less
variation than other transects, but the distribution of the values would best be described as random. The RMS error value for this transect is 20.4%, the highest of all recorded transects.

Figure 21. Contoured resistivity cross section (top) and interpretation (below) along Transect 11. See Figure 18 for location of transect.

Results from Transect 12 also show similar results to 11 with respect to resistivity high location, but the range of resistivities for this transect are much greater. Resistivity values range from 0.3 to 3000 ohm-m at this location. Notable resistivity features occur at 160, 200 and 240 m. At 160 a resistivity low is overlain by a large high resistivity area. Variation throughout the transect seems to be concentrated primarily at the ends of the profile, which consist of alternating highs and lows. The RMS error value after 5 iterations is 15.4%.

Figure 22. Contoured resistivity cross section (top) and interpretation (below) along Transect 12. See Figure 18 for location of transect.
Resistivity data collected at the Dunbridge site were also used to create contour maps for each separation used. As seen in Figure 23, the contours of resistivity changes with depth, displays large variations. Areas with high resistivity differences are shown by the appearance of multiple contour lines. The location of the cavity was marked in the field at approximately 100 m.

Figure 23. Resistivity contour maps of the shallow subsurface. From left to right, images represent 2.5m, 5 m, 10 m, and 15 m separations, respectively. Contour intervals on scales by each map are in ohm-m, while the vertical and horizontal map scales are in m.
DISCUSSION

To standardize the interpretations of the previously described data, resistivity values from 1 ohm-m to approximately 100 ohm-m are considered to be clay soils or possibly water filled bedrock cavities (Burger, 1992). Values that range from 300-1000 ohm-m are considered to be sands and gravels or bedrock. Resistivities higher than this are associated with bedrock and air-filled cavities (Burger, 1992). Transects that contain resistivities consistent with changes in bedrock resistivity or cavities were interpreted based on the surrounding resistivities. For example if the entire profile has high resistivities such as in Transect 6, and there are minor differences within those areas they are considered to be lateral changes in the bedrock resistivity. If resistivity highs were unique to a location such as in Transect 7, then they were considered to be a cavity rather than a change in bedrock resistivity.

Interpretations on soil moisture vs. thickness or composition were made based on the expected locations of the variations. For example, soil composition or thickness is a major factor in the first meter of soil; therefore variations within the first meter of the profile were interpreted as changes in soil thickness, composition and to some extent moisture content. Soils located below the first meter were interpreted as varying primarily in moisture content, as the water table is assumed to be just above the bedrock surface.

Crystal Rock Cave Site

The resistivity variations in Transect 1 (Fig.10) are consistent with a transition from bedrock to an air-filled cavity covered by clay, sand, and silt. The resistivity highs from 100 – 160 m can possibly be an air-filled cavity with a possible collapse structure located directly
above. This structure is identified by the presence of low resistivity values associated with clay sediment and fill that would have occupied the resulting cavity.

Transect 2 (Fig. 11) shows large variations in near-surface resistivity, which could be interpreted as changes in soil composition and moisture. Possible cavities are present in the subsurface at depths of approximately 2.5 m to the maximum profile depth. These cavities show multiple features suspected to be areas of bedrock dissolution, which created bedrock lows, which were subsequently filled by soil.

Transect 3 (Fig. 12) appears to show a series of cavities or changes in the resistivity of the bedrock present at depths of 1.5 m to the base of the profile with a possible transition from air filled to water filled cavities at 70 m and 130 m identified by the area of low resistivity that continues deeper into the subsurface. To the eastern side of the profile, lower resistivity values are thought to represent clays, silts and sands that fill in bedrock lows associated with either collapse structures or dissolved bedrock beneath the series of cavities.

Transect 4 (Fig. 13) has a large variation in resistivity values, the most noticeable of which occurs between 110 and 150 m. This profile is best interpreted as showing near surface variations from probable slight differences in soil composition/moisture content, while also showing the characteristics of the underlying bedrock. From 110 – 150 m. there is a possible collapse structure present, the base of which is below the recorded depth of the transect. Possible air-filled cavities exist at 100m and 160m. Excluding the previously mentioned cavities, higher resistivity variations could possibly indicate changes in the porosity of the bedrock rather than the presence of cavities. Lower resistivity areas beneath these variations could be caused by the presence of water filling voids in the bedrock.
The resistivity high in Transect 5 (Fig. 14) could possibly be bedrock with multiple cavities. To the NE of the profile, what appears to be a bedrock low is visible, as resistivity values characteristic of clays and sands have filled in this area.

Transect 6 (Fig. 15) is interpreted to show multiple cavities from 50 m. to the end of the profile. This transect, along with the possible cavities, also has areas that are best identified (based on established values) as non-porous bedrock or a sandy/gravel fill. At the base of the profile, lower resistivity values are probably representative of the water table, but could be moisture rich clays filling voids.

Transect 7 (Fig. 16) shows resistivity highs that correspond to known cave locations at approximately 200 m, with new locations at the same depth across the transect. Transect 7 does not run directly over the known location, rather to the east of the entrance. It is assumed that the resistivity highs seen here are representative of a buried portion of the same cave system. Variations in resistivity along this profile may reflect lateral changes in the composition of the underlying dolomite rather than the presence of sands and gravels. High resistivity values reflect the amount of secondary porosity of the dolomite or air-filled cavities. Low resistivity values to the right of the profile could indicate the presence of the water table beneath the air-filled cavities.

Transect 8 (Fig. 17) shows Transect 8, which crosses Transect 7 at approximately 200 m, and shows the lateral change from a clay and sandy soil covered location to the top of the known cave system. Resistivity changes in this profile are similar to the resistivity values present on transect 7, clearly identifying the transition from soil covered bedrock or a sand/gravel fill to the bedrock visible at the surface. This change is clearly shown as the transect transitions from low resistivity values to higher values indicating the presence of cavities deeper into the subsurface.
Dunbridge Site

Ignoring the shallow resistivity variations, which are probably caused by variations in soil moisture, porosity, or crop residue, the general pattern seen for Transects 9 – 12 is best described as having an area of low resistivity throughout the mid-depths with areas of higher resistivity on the top and bottom. The low area of resistivity can be interpreted as being compacted clays that are unaffected by the periodic tilling of the surface soils. The higher resistivity area above this layer could be a soil with higher resistivities because of oxidation and higher air content than the surrounding soil. Higher resistivity values below the low resistivities could be attributed to variations within the soil such as intermittent fills (clays and sands), and amplifications of resistivities because of data noise.

For this site, the location of the filled cavity was at approximately 100 m along Transect 11 (Fig. 18). Transect 9 (see Figure 19) was 10 m. from the identified cavity and displays unique resistivity variations at 100 m. Here resistivity variations form an area that clearly looks like a possible pipe of higher resistivity material surrounded by lower resistivity soils. This pattern continues until the base of the profile, where it is assumed that bedrock is found beneath the recorded profile.

Transect 10 (see Figure 20) also displays unique resistivities at 100 m, but unlike Transect 9 resistivity values are high, having a contours that appear elongated vertically, rather than horizontally as in transect 9. The resistivity variation shown here could be due to the changes in the fill above the cavity location. At 120 m, there is another high area of resistivity possibly indicating an area consisting of rocks and loose soil, which would have a higher apparent resistivity.
Transect 11 (see Figure 21) was positioned directly above the center of the filled cavity, which could explain the variations seen at 100 m. Resistivity here appears to be a bowl shaped area of higher resistivity, from 70-100 ohm-m at a depth of approximately 1.5 m. Beneath this area there are lower resistivities consistent with values associated with clay and possibly bedrock; although it is believed that the highs seen beneath this area are caused by amplifications of resistivity values from data noise.

Transect 12 (see Figure 22) shows similar patterns to Transect 11, but at 100 m the resistivities shown are not consistent with the resistivities shown on other transects. When compared to previous transects, similar resistivities are shown to be at 160 m, rather than 100-120 m like other profiles. Beneath this, there is an area of lower resistivity, which again could be described as clay fill overlying bedrock.

The location of the cavity is clearly visible on the contoured resistivity map for the 2.5 m separation (Fig. 23). At 100 m, the steep gradient in resistivity is representative of the variations shown in Transects 9-12, which ultimately are representative of the variety of materials used to fill the cavity. This area of higher resistivity is also visible on the 5 m contour image, although the variation in resistivity is significantly reduced. The structure is not visible in the 10 and 15 m separation contour maps because the resolution of the instrument is too low at these depths.

**Evaluation of Capacitively-coupled Resistivity method**

Overall, the use of capacitively-coupled towed arrays in this area worked exceptionally well in the Crystal Rock Cave site. Using the OhmMapper at this site location allowed us to identify new cavities and areas of interest, which was its primary function. Near surface
variations in this area are at a minimum, but clarity of the data was still not as high as seen in other surveys (Garmon, 2006; Kruse 2006) that were used in sand and gravelly areas.

The use of capacitively-coupled towed arrays was not effective at the Dunbridge site, as it did not clearly identify the presence of the expected cavity, nor was the system able to penetrate effectively to bedrock, as only possible irregularities are visible. Possible explanations for this could be accounted simply by equipment error or failure, human error, or the conductive properties of clay.

According to Walker and Houser (2002) it is possible for the OhmMapper system to accurately measure soil moisture levels when compared to point measurements at the same depth. Given the large variations in resistivity found in this clay rich, farm field area it is reasonable to assume that most of the small changes in resistivity can be explained by changes in soil moisture. Another possible explanation for the large variations in resistivity could be the presence of different types of organic materials near the surface. When the data were collected, the field had been worked using conservation tillage, and winter wheat had already been planted.

Previous studies have shown that resistivity can be a good method for locating buried cavities in karst locations, leading us to make two assumptions. One is that capacitively-coupled systems induce too low of a current in the ground to penetrate completely to the bedrock surface, and the second is that this method should be limited to areas that have a majority composition in the sand and gravel range, with limited or distinct clay variations.

As noted previously, the resistivity properties of clay could have been a determining factor in the ability of the capacitively coupled resistivity systems to accurately collect data. The methods inability to penetrate the approximately 5 m of low resistivity clay to collect data about the bedrock surface limits the OhmMappers’ use in these areas.
Evaluation of OhmMapper Equipment

Problems that occurred at the Crystal Rock Cave site location were limited to general equipment failure, caused by normal equipment use. These issues, which were simple cable replacements, were corrected and surveying continued. Another issue experienced at this site was the difficulty of navigating the towed array around corners. This made completing transects 6 & 7 extremely difficult, as they wind through the area as seen on Figure 9.

Although equipment failure was not an issue at the Dunbridge site, it is possible that faulty cables again could have been responsible for some of the resistivity noise. Human error, although believed to be a limited factor, could account for some of the variations identified near the approximate location of the depression as well as other slight variations throughout the profile. Using the OhmMapper system, data must be collected at the same speed otherwise resistivity values will be incorrectly located along the traverse. While every attempt was made to keep transect speed constant, variations in just one separation of the transect could cause an entire profile to be incorrect.

In order to improve the capacitively-coupled towed arrays for use in clay soils, the equipment design should be designed to handle the stresses associated with data collection. Equipment failure from normal wear and tear was very frequent during the course of this study, which casts some doubt on the accuracy of the data collected. Second, the amount of current induced into the ground by the OhmMapper system needs to be increased, which could allow for longer separations to be used in clay soils, therefore extending the depth of penetration. Finally, integrating a GPS into the data collection system would be invaluable, as this would eliminate the need for human input at every level of data collection. This would significantly reduce the location errors associated with operator input. Using such a method, while it would rely heavily
on initial user input, would virtually eliminate errors due to speed variations mentioned before, and would standardize the profile assuming the initial input was correct.
CONCLUSIONS

This study has shown that while resistivity has the potential to perform well in clay soils, the use of capacitively-coupled towed arrays would not be the preferred method of data collection in this environment. Although this method was effective in finding buried cavities at the Crystal Rock Cave Site, it failed to unambiguously locate the filled cavity at the Dunbridge location. Improvements to this method as outlined in the previous discussions should be attempted to minimize the effects of human error and equipment failure.
REFERENCES CITED


APPENDIX A – Detailed data manipulation procedures for MagMap2000 and Res2Dinv

MagMap2000

1. Import data using the standard G-858 method as outlined in the product manual
2. Correct data by deleting erroneous data points identified in the field dataset by selecting data point, right click, and delete position.
3. Despike data by using the despike feature in MagMap2000 under the filter menu.
4. Right click on transect area, select display OhmMapper readings.
5. With OhmMapper readings displayed, select filter, smooth readings with spline. Use the preview button to try a few different settings. 1 usually works the best, without removing too much information.
6. After smoothing with spline, close the readings page. Click File, export to export to Surfer format.
7. To export to Res2D, click and drag across all data lines. With every point selected right click and select Draw Pseudosection.
8. When prompted, select to draw profile along Y axis.
9. With the Pseudosection window selected, go to File, export file to export to Res2D.
10. When prompted, use average direction, and average as the averaging method rather than median.
11. When asked to provide file name make sure to include .dat at the end of the file name.

Res2DInv

1. To read data file, select File, Read data file.
2. Once data file has been read and successfully loaded, click edit, exterminate bad data points. This will open the edit data window. Bad data points are represented on this screen as points that are obvious outliers to the rest of the data points. To remove these points simply left click on them. They will turn red, which is the default color to represent removed data. Upon exiting the window the program will ask to save the edited data.
3. Following the previous editing session, click edit again, and select change electrode first position. Using this editing option will allow you to change the first electrode position to standardize horizontal scales on data profiles. When using the OhmMapper, the first electrode position is often a negative number based on the final separation distance used. For example, a final separation of 40 m often has a first position of approximately -52 m. If the data also has topography you can set that to a number of your choice as well. As with exterminating bad data points you will need to re-save your data set.
4. In order to obtain the best model for the dipole-dipole data sets, settings were changed from the program defaults by selecting Change settings. A special note: It is important
that when changing settings for inversions that you double check the settings. If you close the program and then open it again, default settings will be applied rather than your previous settings. If you wish to use the same settings on all transects, it is possible to save the inversion parameters selected by clicking, change settings, save inversion parameters. This is a useful feature, but remember that inversion settings that obtain the best model for one data set may not obtain the best model for another set. This being said, it is also important to remember that if you have to select parameters for one profile that you do not need on the next, that you must manually remove those parameters.

5. The first setting to change for each data set was the inversion damping parameters. Initially, the optimize damping factor was selected. If while running the inversion, the program noted instability, the damping factor was manually increased to a larger value.

6. To manually control the damping factors, select change settings, inversion damping parameters, damping factors. Here you can change the initial damping factor, minimum damping factor, and the first layer damping factor. Normally, default settings are used. If after running the inversion process you notice that the first layers of the profile appear wavy, use a higher first layer damping factor. For the purposes of this project, a default value of 2.5 was used and increased until the relic was removed.

7. The next setting to change was the mesh refinement option under the change settings, mesh parameters heading. Here the finest mesh was used and 4 nodes per electrode were used. Using this setting compared to a normal or fine mesh with 2 nodes per electrode allows for more accurate calculated resistivity values. A downside to using this setting is that more computer memory is required to complete the inversion process. It should also be noted that use with model refinement will automatically change the setting from 4 nodes to 2, but leaves the setting for the mesh quality.

8. The rest of the available options under the change settings heading were left unchanged as program default settings.

9. Options used under the inversion heading included smoothing, robust inversion, type of optimization method and model refinement. To access these options click on the inversion heading.

10. Under the inversion method and settings subheading, you will find the robust inversion option. Robust inversion was used to more accurately identify areas of interest such as bedrock and resistivities that end abruptly. Following the dialog box that opens up when selected was all that I used to select the robust inversion method. I did not use any of the other options in this window except for the robust constraints.

11. Also under the inversion method and settings is the smoothing of model resistivity. This was only used when suggested by the program, as it smoothes very noisy data by applying a smoothness constraint directly to the model resistivity values.

12. Under the type of optimization method, there is the option to use the incomplete Gauss-Newton method. This method was only applied to the data when suggested by the
program in order to reduce the time taken to create the inversion model. The default convergence value of 0.005 was used in all applications.

13. Finally, model refinement is found under the subheading Model Discretization. Model refinement uses an electrode spacing which is equal to half the unit spacing. Using a model with a narrower cell width provides better results than the normal spacing. This was used on every transect in order to achieve the best results possible. During the running of these profiles, inversions became increasingly long, and the program became unstable. After conferring with the makers of the software, it was identified that model refinement causes the minimum electrode spacing to change from 2.5 m to 1.25 m, cutting it in half each time a data set was saved following an inversion. In order to remedy this problem, a text editor was used to manually change the minimum electrode spacing back to 2.5 m. For interpretations of the structure of raw data, refer to the Res2DINV manual.

14. Following all of the changes in settings and applying the correct options, click on the least squares inversion, under the inversion heading. The program will then ask you to save an inversion file, and then begin the inversion process. All transects were stopped at a maximum of 5 iterations or until the minimum RMS convergence limit was reached. If the program suggested that the inversion process was becoming unstable, or that values were unrealistic, the process was stopped, and damping factors were raised.

15. Following the inversion process, click on display, show inversion results. This will open up the data display window. The program will automatically read the inversion result from the previously read data file. If you wish to read a different inversion file, select read file with inversion results, under the file heading. To display the results select the display sections heading, display data and model sections. This will prompt you to which iteration you would like to see, and also ask which contours you would like the data displayed in. Models always displayed the final iteration, in logarithmic contour intervals.

16. In order to check the accuracy of the model, select the edit data heading. Using this option will bring up an RMS error statistics window. Using the arrow keys, any data points with an error value of over 70% were eliminated. It is possible to interpolate the bad data points with surrounding correct measurements, but I chose to eliminate the bad data. Following the editing, the file was saved and the inversion process was completed again. This process increases the accuracy of the model while removing extremely high error data.

17. If you would like to change the display settings of the program, use the variety of options listed under the change display settings heading. A linear depth scale was used in each of the profiles created for this project. Locations of the datum points were removed from the transects and contours were left in the profile.