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Imaging in karst terrain using electrical resistivity tomography

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IMAGING IN KARST TERRAIN USING

ELECTRICAL RESISTIVITY TOMOGRAPHY

by

IANA MUCHAIDZE

A THESIS

Presented to the Faculty of the Graduate School of the
MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY
In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN GEOLOGICAL ENGINEERING

2008

Approved by

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Richard W. Stephenson
ABSTRACT

The Missouri Department of Transportation (MoDOT) plans to construct a new intersection between highway 60 and highway 65 to alleviate traffic congestion during peak flow periods. This construction site, which is referred to as the Route 60/65 study site in this thesis, is located on the southeastern side of Springfield, Greene County, Missouri. Bedrock in the study area (Burlington-Keokuk Limestone) is characterized by karstic features such as loosing streams, underground caves, and sinkholes. Prior to the commencement of construction, MoDOT conducted a study of the subsurface conditions in the Route 60/65 study site. The main objective was to identify features, such as air-filled voids and solution-widened joints, which could create the potential problems in terms of the immediate and long term serviceability of the intersection. Information about variable depth in bedrock also was required.

Karst terrains are characterized by highly irregular subsurface conditions. Borehole control alone provides accurate data only at the sampling location, so control elsewhere has to be interpolated, which can result in erroneous assumptions. To overcome this problem, geophysical data can be acquired between boreholes. Implementing of engineering geophysics as an additional tool allows better resolution of the subsurface condition, when constrained with ground truth information. It also decreases the required number of boreholes and accordingly saves time and money for the site characterization part of the project.

For this project, the Electrical Resistivity Tomography (ERT) method was employed. The Dipole-Dipole multi-electrode array was utilized because it generally provides the best resolution in areas with highly variable depth to bedrock. On the basis of ERT interpretations the following conclusions were drawn:

- All solution associated features and depth to bedrock were mapped.
- Air-filled voids were not identified on the Route 60/65 ERT data set.
- Geophysical interpretations were constrained by ground truth information available for the Route 60/65 study site.
ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my advisor, Dr. L. Neil Anderson, for patiently guiding me throughout my graduate study in general and my research in particular. His guidance and support helped me to excel my knowledge and professional skills.

I would also like to thank Dr. Richard W. Stephenson and Dr. David J. Rogers for serving on my committee and providing insightful comments.

Special thanks go to my parents, my husband and all my friends who have always believed in me and gave me strength to accomplish my goals.
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1. INTRODUCTION

1.1. SITE DESCRIPTION AND OBJECTIVE

The study site is located immediately north and west of the intersection of highways 60 and 65, within the southeastern limits of the city of Springfield in Greene County, Missouri (Figures 1.1 and 1.2). The location of Springfield relative to the Kansas and Arkansas state lines is shown in Figure 1.1.

![Map showing location of Springfield relative to Arkansas and Kansas border line](image)
The study site is immediately north of existing highway 60. It is an open area with little vegetation, covered by a blanket of loosely consolidated residuum soil. The maximum and minimum elevation of the site is about 1300 ft/396.2 m and 1220 ft/372 m. The geophysical investigation was conducted during the second half of January and the average temperature was about 32 degrees F.

The Missouri Department of Transportation (MoDOT) intends to build a new off-ramp from highway 65 to highway 60. The objective is to alleviate traffic congestion, especially during rush hour. Further in this thesis the area of interest is referred to as the Route 60/65 study site.

Figure 1.2. Map of Springfield, Greene County, showing the location of the Route 60/65 study site. A: Fantastic Cavern Site, 4872 N Farm Road 125, Springfield, MO indicated as a purple star. B: Crystal Cave, 7225 E Crystal Cave, Springfield, MO indicated as a blue star.
Greene County is well known for the presence of karstic features such as caves, springs and, more importantly, sinkholes. In Greene County more 2500 sinkholes and 245 caves have been found, (Greene County Comprehensive Plan, page 52, 2007). Several such features are in the close proximity to city of Springfield; two caverns are shown in Figure 1.2, and indicated as letters A and B. A well-developed system of underground caverns creates the potential for developing new sinkholes. Clay-infilled cutters (solution widened-joints/fractures) can cause differential settlement of above laying materials.

One of MoDOT’s objectives was to determine whether geotechnical mitigation efforts were necessary prior to construction of the new ramp. MoDOT needed information on the depth of bedrock and potential problems with air filed cavities and dissolution- widened joints that could undermine the integrity of the planned structure.

According to conventional geotechnical procedures, a suite of boreholes were to be drilled prior to the construction of the new intersection. The bedrock in the Route 60/65 study site is highly dissolved Burlington-Keokuk Limestone, and can be characterized by presence of pinnacles and cutters (Fellows, 1970), meaning that the depth in bedrock generally varies greatly. If detailed subsurface information was acquired using boreholes only, they (boreholes) would have to be closely spaced in order to come up with a reliable image of the subsurface. Unfortunately, such drilling is time consuming and expensive. Also, even though the subsurface information obtained at boring location is very accurate, the interpolation between boreholes can sometimes be erroneous due to significant lateral variability in karst terrains.

Electrical Resistivity Tomography data acquisition of complementary geophysics control provides for superior results (understanding of subsurface). Geophysical control reduces the number of required boreholes and significantly decreases ambiguity (subsurface conditions) especially between boreholes. In this project, the Electrical Resistivity Tomography method was used to better delineate subsurface conditions. This method has proven to be an effective tool in areas with highly variable elevation of bedrock.

The Geophysical Laboratory of Missouri University of Science and Technology (MS&T) was asked to investigate the Route 60/65 study site and come up with a reliable
and detailed subsurface model that depicted variable depth in bedrock. A model of zones where karst features were present, such as air filled voids and areas of intensive dissolution, were also needed. In addition, geophysical group also was asked to identify sites for follow-up borings.

1.2. GEOLOGIC OVERVIEW OF STRATIGRAPHIC UNITS IN SPRINGFIELD, GREENE COUNTY, MISSOURI (BASED ON WORK OF JERRY D. VINEYARD AND JAMES E. VANDIKE)

Approximately 520 million years ago during the mid to late Cambrian Period the Ozark area (southern part of Missouri) started to subside. The shallow Lamotte Sea began to inundate the area, and Missouri became part of a shallow marine shelf that extended from New York to Mexico. Since then, sedimentary strata of more than 2700 ft / 823 m were deposited below the streets of Springfield, Greene County.

The geologic and stratigraphic units of Greene County are listed in Table 1.1. As indicated in Table 1.1, three sedimentary rock Systems (Cambrian, Ordovician, and Mississippian) were deposited on top of crystalline rock belonging to the Precambrian System.

As the shallow sea started advancing northward, coarse-grained sediments comprised of quartz sand and crystalline rocks fragments were deposited over the crystalline Precambrian System (Table 1.1). The first Formation in the sequence of the Cambrian System is the Lamotte Formation. This formation consists of quartzose sandstone and its thickness is approximately 150 ft / 45 m. The overlaying unit is the Bonneterre Formation, with thickness of approximately 200 ft / 70 m. This formation is comprised mostly of medium- to fine-grained dolomite. The Bonneterre Formation is followed by the Davis Formation, which is composed of shale intermixed with dolomite. The unit’s thickness is about 150 ft / 45 m.

After the Davis Formation was deposited, a long period of deposition dominated by clean carbonate rock began. During the following period of time, the Derby-Doerun, Potosi, and Eminence Formations were deposited (Table 1.1). Clean dolomite with a small amount of chert is the primary rock type for all three formations. The total
thickness of these three formations is about 500 ft / 150 m. The end of deposition of the Eminence Formation concludes the Cambrian System in the Springfield area.

Table 1.1. Geologic and Stratigraphic Units in Greene County (Vandike, 1993)

<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Group</th>
<th>Formation</th>
<th>Thickness (ft)</th>
</tr>
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<tbody>
<tr>
<td>Mississippian</td>
<td>Osagean</td>
<td></td>
<td>Burlington- Keokuk Formation</td>
<td>150-270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Elsey Formation</td>
<td>25-75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reeds-Spring Formation</td>
<td>125</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pierson Formation</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>Kinderhookian</td>
<td>Chouteau</td>
<td>Northview Formation</td>
<td>5-80</td>
</tr>
<tr>
<td></td>
<td>Kinderhookian</td>
<td>Chouteau</td>
<td>Compton Formation</td>
<td>30</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Canadian</td>
<td></td>
<td>Cotter Formation</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>Canadian</td>
<td></td>
<td>Jefferson-City Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Roubidoux Formation</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Upper Gasconade Dolomite</td>
<td>350</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower Gasconade Dolomite</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gunter Sandstone Member</td>
<td>25</td>
</tr>
<tr>
<td>Cambrian</td>
<td>Upper</td>
<td>Elvins</td>
<td>Eminence Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Potosi Formation</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Derby-Doerun Formation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Davis Formation</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bonneterre Formation</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lamotte Formation</td>
<td>150</td>
</tr>
<tr>
<td>Precambrian</td>
<td></td>
<td></td>
<td>Crystalline rock</td>
<td></td>
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The Cambrian System in southwest Missouri is overlain by the Ordovician System, which is represented by the following geologic units: Gasconade Formation, Roubidoux Formation, Jefferson-City Formation and Cotter Formation. The basal unit in the Ordovician System, the Gasconade Formation, is comprised of three members: Gunter Sandstone, Lower Gasconade Dolomite, and Upper Gasconade Dolomite. The total thickness of the Gasconade Formation is about $375 \text{ ft} / 114 \text{ m}$, and it is mostly comprised of interbedded sandy dolomite, cherty dolomite, and quartz sandstone. The Gasconade formation is overlain by the Roubidoux Formation, with a thickness of $150 \text{ ft} / 45 \text{ m}$. This Formation mostly consists of dolomite, but has some inclusions of chert. In some locations the Roubidoux Formation is interbedded with layers of sandstone.

The environment changed and carbonate rocks became predominant after the Roubidoux Formation. The deposition of Ordovician Age rocks continued with the deposition of two more Formations: Jefferson-City and Cotter. The total thickness of these two Formations is about $600 \text{ ft} / 183 \text{ m}$. The Cotter Formation finalizes the Ordovician System in Greene County (Bullard et al., 2001).

The Ordovician System is overlain by the Mississippian System (Table 1.1), which in Greene County is represented by the Compton, Northview, Pierson, Reeds Spring, Elsey, and Burlington-Keokuk Formations. The total thickness of this System is about $640 \text{ ft} / 195 \text{ m}$.

The Mississippian System starts with the Compton Formation, which has a thickness of less than $30 \text{ ft} / 9 \text{ m}$. The Compton Formation is overlain by the Northview Formation with the average thickness up to $80 \text{ ft} / 25 \text{ m}$. It is represented here by brown siltstone and blue or bluish-green shale. The Mississippian System continues with the deposition of the Pierson, Reeds Spring, and Elsey Formations. The total thickness of these three formations is about $260 \text{ ft} / 79 \text{ m}$. Cherty limestone is a dominant component in all three Formations.

The deposition of the Mississippian System is finalized by the Burlington-Keokuk Formation. This is the youngest rock unit exposed in Greene County. The thickness of this Formation is approximately $270 \text{ ft} / 82 \text{ m}$, and it consists of fossiliferous limestone and cherty limestone. The majority of springs and caves in Greene County are found in Burlington-Keokuk Limestone.
The geophysical investigation was focused on upper Mississippian Age rocks, and the following text is a discussion of the late Mississippian deposition.

1.2.1. Overview of Stratigraphic Succession of Mississippian System in Springfield, Greene County, Missouri. The stratigraphic succession of rock units in the Mississippian System is not uniform throughout Missouri; so to facilitate a description of Mississippian Age rocks, Missouri was divided into six zones: northwestern, east-central, southeastern, central, southwestern, and northwestern (Figure 1.3) (Vineyard, 1992).

Figure 1.3. Regional distribution of the Mississippian System in Missouri (Vineyard, 1992)
Figure 1.3 shows that the Route 60/65 study site (Springfield, Greene County) is located in the southwestern region. The geologic map that indicates the surficial distribution of the outcropping geological Formations in this region is shown in Figure 1.4. The area of research is highlighted by a red arrow.

![Image of geologic map showing the Route 60/65 study site in Springfield, Greene County.](image_url)

**Figure 1.4.** Bedrock geologic map of the southwestern area of Springfield (Middendorf, 1991)

In the Route 60/65 study site, the shallow subsurface is mainly represented by rocks of Osagean Series, Mississippian System. As was stated in Section 1.2, Mississippian System is represented here by the Pierson, Reeds-Spring, Elsey and Burlington-Keokuk Formations. These four formations have similar lithologic
characteristics, and it is difficult sometimes to differentiate them. It is customary to group these four Formations into two collective units (Figure 1.4):

1. *(Mlo)*, Elsey, Reeds Spring and Pierson Formations (Lower Mississippian, Lower Osagean),

2. *(Muo)* or *(Mbk)*, Burlington and Keokuk Formation (Lower Mississippian, Upper Osagean).

Geological Survey and Water Resources – Galloway Quadrangle, Greene County, Missouri, by Larry D. Fellows 1970

The following text is a detailed description of lithology for the rock units in Mississippian System in the Route 60/65 study site (based on the work of Middendorf, 1991).

### 1.2.2. Elsey, Reeds Spring and Pierson Formations *(Mlo).*

The Elsey Formation is light-gray, crystalline to micritic limestone with chert fragments and some crinoids; chert locally constitutes about 60 percent of the Elsey Formation.

The Reeds Spring Formation is gray to brown; finely crystalline limestone with chert fragments; chert locally makes up about 40 of the Reeds Spring Formation.

The Pierson Formation is comprised of brown to brown-gray magnesian limestone with chert nodules. The fine-grained matrix contains some fossil fragments (Middendorf, 1991).

### 1.2.3. Burlington – Keokuk Limestone *(Muo)* or *(Mbk).*

The Burlington - Keokuk Limestone is the most important Formation in this thesis, because the bedrock in the Route 60/65 study site is the Burlington-Keokuk Limestone (Figure 1.5) and geophysical data were acquired from this Formation.

Burlington–Keokuk Formation is coarse– to medium-grained, light gray limestone with some chert nodules. The limestone is comprised almost entirely of crinoid fragments. The Burlington-Keokuk Formation weathers to a red to reddish brown residual soil that contains a variable amount of chert fragments. The Burlington-Keokuk Limestone almost entirely comprised of pure calcite, thus this Formation is susceptible to weathering through dissolution process. Uneven dissolution of this Formation has resulted in highly irregular bedrock-overburden interface (Fellows, 1970).
Figure 1.5. Stratigraphic column for the Route 60/65 study site (Fellows, 1970)

Lateral distribution of Mississippian Age Formations throughout the southwest of Greene County is illustrated in Figure 1.6. The cross section was prepared for line A-A’ (Fellows, 1970).
Figure 1.6. Generalized cross section A-A’ (Figure 1.4.), Green County, MO, illustrates lateral extension of Mississippian Age Formations (Fellows, 1970)
1.3. OVERVIEW OF SURFICIAL DEPOSITS IN SPRINGFIELD AREA (BASED ON WORK OF L. D. FELLOWS)

Soils across the area of interest are predominantly residuum. Residuum is unconsolidated sediment formed by chemical and mechanical weathering of underlying bedrock (Burlington-Keokuk Limestone). Residual soil in southwestern part of Greene County is red to reddish-brown residual clay with admixed chert fragments. The thickness of residuum varies greatly. According to MoDOT borehole control, overburden can be as thin as 4.7 ft / 1.4 m, and at some locations the bedrock is at depth of 41.4 ft / 12.62 m.

Depth in bedrock is highly variable because of the presence of pinnacles and cutters, which is caused by weathering (dissolution) and erosion. Due to differential compaction, residuum is commonly draped over pinnacles (Figure 1.7). Locally, residuum is porous and permeable, and water easily moves through it (Fellows, 1970).

Figure 1.7. Generalized diagram showing relationship between superficial deposits and bedrock formations (Fellows, 1970)
1.4. STRUCTURAL DEFORMATION OF MISSISSIPPIAN AGE ROCK IN THE ROUTE 60/65 STUDY SITE

Bedrock where the geophysical investigation was conducted is intensively jointed and fractured. Intensive fracturing is caused by the crustal deformation within Mississippian Age rock. The following chapter and Figure 1.8 describe several structural features found in relative proximity to the Route 60/65 study site (the Route 60/65 study site is indicated by red arrow). It can be seen from Figure 1.8 that all of Greene County is dissected by sets of faults and joints. The horizontal orientation of these features is nearly orthogonal. The most of discontinuities in Greene County exhibit NNW and ENE strike orientation, Figure 1.8.

The crustal deformations here were provoked by vertical and horizontal movements of the upper crust, due to either orogenic processes or differential subsidence. Internal stresses induce gradually increasing strain, which results in fracturing of brittle rocks. After series of uplifts and downward movements of the strata, the uniform horizontal extent of sedimentary rock formations is disrupted, and resulted in development of such structures as folds, faults and joints.

1.4.1. Faulting (based on work of D. Fellows, 1970 and M. McCracken, 1971).

According to M. McCracken, the faults of the Ozark region are a result of the reactivation of preexisting deep-seated faults extending into the Precambrian basement. There are three structural features associated with the faulting in the area of study: Pearson Creek Fault System, Kinser Bridge Fault, and Danforth Graben (Fig 1.8), all of which have northwest – southeast trend and exhibit a normal displacement. Faulting is prevalent in Mississippian Age rock and older because the brittle carbonate beds tend to fail primary by fracturing rather than by folding (M. McCracken, 1971).

**Pearson Creek Fault System** – the strike orientation of this fault system is N. 55º W. and normal displacement of about 10 to 20 ft /3 to 7 m.
Location: the system extends northwesterly from Sec. 6, T. 28 N., R.20 W., to Sec. 35, T. 29 N., R.21 W., Greene County Missouri (McCracken, 1971), (Figure 1.8).

**Kinser Bridge Fault** – this fault is estimated to have a displacement of 50 ft /15.24 m. The fault trends west-northwest.
Location: it extends from Sec. 3, T. 28 N., R.21 W., into Sec. 7, T. 28 N., R.20 W., Greene County Missouri (McCracken, 1971), (Figure 1.8).
Danforth Graben – is a down dropped block, 0.15 to 0.25 mile wide /0.24 to 0.4 km wide. Vertical displacement is about 70 ft /21.34 m. Location: it extends from Sec. 16, T. 29 N., R.20 W., northwestward to Sec. 1, T. 29 N., R.21 W., Greene County Missouri (McCracken, 1971), (Figure 1.8).

1.4.2. Joints. Joints, also known as fractures, are another common structural feature similar to faults. An exception is that the lateral and vertical displacements are absent. Joints can be seen in consolidated rocks (Figure 1.12), which are more rigid and less flexible.

According to Mary McCracken almost all consolidated rocks in Springfield, Greene County are intensively jointed/ fractured. Fractures/joints are nearly orthogonal and exhibit two general strike orientations: N. 20 ° W., and N. 60 ° E. (Figure 1.8), and dip about 90 °. At different locations the strike orientation can be slightly different from the one described by McCracken. To define orientation of joints/fractures within the area of study, the neighboring areas can be investigated for presence of outcrops, springs and
The Sequiota Spring, one of the larger springs in the Springfield area, is located in the Galloway quadrangle, NE ¼, NW ¼ sec. 9, T. 28 N., R. 21 W., Figure 1.9. Sequiota Spring is also known as Fisher Cave. The spring flows from a cave developed on a system of orthogonal joints, widened along a bedding plane in the Mississippian Burlington-Keokuk Limestone. The cave’s entrance is about 8 ft /2.4 m high and 30 ft /9.1 m wide (Vineyard, 2001).

Two smaller caves are present to the left from the main entrance of the Sequiota Spring (Figure 1.10). Caves usually form along solution widened bedding planes and
vertically oriented joints/fractures, thus the orientation of these caves can be used for delineation of the common trending of joints and fractures for a given area. The orientation of cave passage was measured for both caves and the joint orientation was established as N. 16 º W (Figure 1.11 and Figure 1.12). This orientation was consistent with the direction of fractures that were found in a massive Burlington-Keokuk Limestone outcrop next to the spring. Fractures present in the Burlington-Keokuk Limestone were nearly orthogonal and of two directions.

Figure 1.10. Sequiota Spring Springfield, Greene County, Missouri
The measured directions are: N. 16 º W and N. 68 º E (Figure 1.11 and Figure 1.12)
Figure 1.11. The direction of joint in Burlington-Keokuk Limestone, Sequiota Spring

Figure 1.12. Nearly orthogonal directions of joints in Burlington-Keokuk Limestone, Sequiota Spring
2. THEORY OF FORMATION OF KARST FEATURES WITH EMPHASIS ON GREENE COUNTY, MISSOURI

According to Missouri Department of Natural Resources dictionary, karst is “a type of topography that is formed on limestone, gypsum, and other rocks by dissolution, and is characterized by sinkholes, caves, and underground drainage”.

The general representation of U.S. karst areas published by AGI (Veni et al., 2001) Figure 2.1, indicates that almost all southern Missouri is underlined by carbonate rock and recognized as a karst terrain (shown in green color at the map, Figure 2.1).

In the Route 60/65 study site, bedrock is the Burlington-Keokuk Limestone. It is known as to be jointed and fractured. Joints serve as natural passageways for slightly acidic meteoric water. As water percolates through limestone, it dissolves away soluble substance leaving behind widened fractures and bedding planes. In such a way, a labyrinth-like system of passageways is formed. Over time, openings within the rock increase in size and underground drainage systems start to develop.

The carbonate rocks limestone and dolostone are predominantly composed of calcite mineral (CaCO$_3$) and dolomite mineral (CaMg (CO$_3$)$_2$), and both, especially calcite, are susceptible to dissolution when slightly acidic water acts on them. Meteoric water absorbs carbon dioxide (CO$_2$) from atmosphere and thus becomes slightly acidic. After meteoric water reaches the ground, it passes through soil that may increase CO$_2$ concentration. At the point where water reaches beds of carbonate rock, it starts to react with soluble minerals. Dissolved matter will be washed away, and as a result, features such as dissolution-widened joints, and air-filled voids start to form.

Missouri is widely known as “The state of caves”. There are several major karst areas found St. Louis, Ste. Genevieve, Cooper Boone Christian and Greene Counties.

The highest number of caves is found in the Mississippian Age rocks. According to the statistics (Vineyard, 1992), the dolomites and limestones of this Age accommodate about 1.475 caverns in the state of Missouri.

Many caves are deep below the general land surface. In fact, the deepest known cave in the Missouri is 383 ft / 117 m deep (Vineyard, 1992). Other caves are present at a shallower depth. The latter have thinner layers of overlying material, and are more prone
to collapse leaving segments of the underground cave system open to daylight; such openings are widely known as sinkholes.

Sometimes sinkholes “open” without any warnings and cause a serious damage to overlying structures. Even in rural areas, the formation of sinkholes may create potential problem for farming. Such openings also provide direct access for contaminants to groundwater depository, and further contamination of potable water may be initiated.

Figure 2.1. Karst map of the US published by AGI (Veni et al. 2001)

The illustration below (Figure 2.2) shows an opening of a sinkhole in Nixa, Greene County Missouri. As Figure 2.2 illustrates the cost of sinkhole collapse can be reflected not only in a financial loss, but also in loss of life (fortunately all tenants of a structure in Figure 2.2 are safe).
The structure in Figure 2.2 was built above a soluble carbonate rock covered by clayey residuum. According to geophysical investigation, the Nixa sinkhole developed near the intersection of two nearly orthogonal solution-widened joint sets (N. Anderson).

There may be more than one factor causing developing of sinkhole or ground subsidence. One of the most common is a presence of migrating groundwater through soluble rock. Another factor is the fluctuating groundwater table. Withdrawal of large amounts of water leads to decrease in the ground water table, which can be followed by ground subsidence. Sometimes, changing in loading such as excavation or placement of fill can trigger collapse of a cave’s roof, and the appearance of sinkhole.

Figures below (Figure 2.3 and Figure 2.4) illustrate stages of a sinkhole formation. (The diagrams below were extracted from the Missouri Department of Natural Resources web site).
Stage 1: For a sinkhole to form there must be a discontinuity within the bedrock, such as dissolution-widened joint or fracture that allows overlying soil to move downward into already existing solution-widened bedding plane/conduit that allows groundwater to flow.

Stage 2: Soil that accumulated in the conduit in Stage 1 has been washed away by groundwater flow.

Stage 3: Soil accumulated within the dissolution-widened fracture has collapsed into the conduit and washes away by groundwater flow.

Stage 4: Soil is not supported now, but is driven by force of gravity continue to collapse into the opening leaving a void within the soil layer.
Figure 2.4. Stages of a sinkhole formation (5-8)

Stage 5: With time, the void enlarges and moves toward the surface.

Stage 6: Eventually only a thin layer of soil, known as a roof, remains at the surface. Addition of load from above may accelerate the process of sinkhole opening.

Stage 7: Finally, the soil roof can no longer support itself and collapses.

Stage 8: If the fracture within the bedrock remains plugged with the collapsed material, the sinkhole may be filled with other eroded soil

One of the reasons the geophysical survey was conducted for the Route 60/65 study site was to obtain conclusive information about subsurface conditions. MoDOT needed to be aware of any potential problem features like those described in this chapter.
3. LITERATURE REVIEW: ELECTRICAL RESISTIVITY TOMOGRAPHY

Electrical Resistivity Tomography (ERT) has been used for decades as an effective geotechnical and environmental engineering tool. In particular, ERT methodology is widely used for determining depth of bedrock, location of contaminated plumes, acquiring information on elevation of groundwater table, etc. This method is especially preferred for sight characterization in karst terrains (W. Zhou, 1999). When Electrical Resistivity Tomography data is used in combination with exploratory borehole, the cost and the time necessary for the project can be significantly reduced. When the geophysical data are constrained by borehole control, they can provide accurate and high-resolution interpretations. In addition, the use of this geophysical method can be of a great help in terms of siting additional borehole control.

- Electrical Resistivity Tomography techniques were successfully used in the following published papers:
  - Interpretation of Electrical Resistivity and Acoustic Surface Wave Data Acquired at Nixa Sinkhole Study Site by Neil L. Anderson.
  - Assessment of Karst Activity at Clarksville Study Site by Jon Robinson and Neil L. Anderson.
  - Investigation of Bridge Foundation Sites in Karst Terrains via Multi-Electrode Electrical Resistivity by Dennis R. Hiltunen and Mary J. S. Roth.
  - Three-Dimensional Electrical Resistivity Surveys to Identify Buried Karst Features Affecting Road Projects by K. Michael Garman and Scott F. Purcell.
  - Effective Electrode Array in Mapping Karst Hazards in Electrical Resistivity Tomography by Wanfang Zhou, Barry F. Beck and Angela L. Adams.
  - Electrical Imaging Surveys for Environmental and Engineering Studies by Dr. M. H. Loke.

• Two-Dimensional Resistivity Imaging Survey for Detecting Termitaria in a Dam by Haobin Dong, Chuanei Wang, Huaping Wang, and Xinhui Cai, C. Richard Liu.

• Electrical Resistivity Techniques for Subsurface Investigation by Steve Cardimona.

In comparison to the geotechnical site investigation techniques such as trenching and borehole drilling, electrical resistivity tomography is more rapid, relatively more inexpensive, and less labor-intensive. In karst terrains where lateral variations in the depth of bedrock vary greatly, interpolation of the subsurface conditions between two boreholes can often provide erroneous results. The use of ERT can provide more precise information on ground conditions between borehole locations.

The main benefit of the ERT technique is that the data can be obtained without interruption of integrity in the investigated objects.

There are several disadvantages of utilization of ERT. The methodology of ERT requires planting of electrodes into the ground. Thus in cases where the study area is covered by concrete or asphalt it is really challenging to take resistivity measurements. Another disadvantage is that the vertical resolution of the processed electrical resistivity data decreases with depth.

The following section describes the basic concepts behind some of the geophysical techniques that were used in this project.

### 3.1. CURRENT FLOW IN THE SUBSURFACE

Electric current flow in the subsurface is primarily electrolytic. Electrolytic conduction involves passage of charged particles by means of ground water. Charged particles move through liquids that infill the interconnected pores of permeable mass of soil (Robinson, 1988).

When Electrical Resistivity Tomography surveying is conducted in karst terrain, current flow is generally assumed to be via electrolytic conduction.
3.2. RELATIONSHIP BETWEEN GEOLOGY AND RESISTIVITY

Variations in the resistivity of subsurface materials are mostly a function of lithology. Information about resistivity variations within the subsurface can be associated with different materials. Some of resistivity values are given in the Table 3.1 (W. M. Telford, 1976).

<table>
<thead>
<tr>
<th>Earth Material</th>
<th>Resistivity, Average or Range (ohm-m)</th>
<th>Earth Material</th>
<th>Resistivity, Average or Range (ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>$10^2$-$10^6$</td>
<td>Sandstone</td>
<td>$1$-$10^8$</td>
</tr>
<tr>
<td>Diorite</td>
<td>$10^9$-$10^3$</td>
<td>Limestone</td>
<td>$50$-$10^7$</td>
</tr>
<tr>
<td>Gabbro</td>
<td>$10^3$-$10^6$</td>
<td>Dolomite</td>
<td>$10^2$-$10^4$</td>
</tr>
<tr>
<td>Andesite</td>
<td>$10^2$-$10^4$</td>
<td>Sand</td>
<td>$1$-$10^3$</td>
</tr>
<tr>
<td>Basalt</td>
<td>$10$-$10^7$</td>
<td>Clay</td>
<td>$1$-$10^2$</td>
</tr>
<tr>
<td>Peridotite</td>
<td>$10^2$-$10^4$</td>
<td>Brackish water</td>
<td>$0.3$-$1$</td>
</tr>
<tr>
<td>Air</td>
<td>$\sim^0$</td>
<td>Seawater</td>
<td>$0.2$</td>
</tr>
</tbody>
</table>

As seen in the Table 3.1, most materials can be characterized by resistivity values that vary by several orders of magnitude. For example, limestone has resistivity values ranging from 50 ohm-m to $10^7$ ohm-m. Most minerals are considered to be insulators or resistive conductors. So the majority of rocks electrical current flow is accomplished by passage of ions in pore fluids (electrolytic conduction). The conductivity, which is reversal of resistivity, is mostly affected by porosity, saturation, salinity, lithology, clay content and at some degree by temperature. Accordingly, material with constant mineralogical composition can possess different resistivity values, depending upon all above mentioned parameters.
3.3. THE OHM’S LAW AND RESISTIVITY

The following text is a brief review of fundamentals Ohm’s Law and resistivity as they relate to the ERT method.

In 1827, Georg Simon Ohm derived empirical relationship between the resistance ($R$) of a resistor in a simple series circuit, the current passing through the resistor ($I$), and the corresponding change in potential ($\Delta V$):

$$\Delta V = R \times I$$  \hspace{1cm} (3.1)

A simple series circuit that consists of a battery connected to a resistor (cylindrical-shaped body with uniform resistivity) by a wire demonstrates this relationship (Figure 3.1). By using Ohm’s Law, the value of resistance ($R$) can easily be calculated by plugging values of voltage ($\Delta V$) and current ($I$) in the equation (3.1). The last two values are given because they can be measured. The Electrical Resistivity Tomography concept is based on this empirical relationship (Equation 3.1), with the assumption that the resistor in the circuit (Figure 3.1) is the Earth.

There is another relationship that defines resistance ($R$) as a function of geometry of a resistor and the resistivity of the cylindrical-shaped body:

$$R = \frac{\rho \times L}{A}$$  \hspace{1cm} (3.2)

This equation shows that the magnitude of resistance is affected by length ($L$) and the cross-sectional area ($A$) (Figure 3.1) of the cylindrical-shaped body through which electrical current flows (resistor). A factor that defines the ease for electrical current to flow through the media is known as resistivity ($\rho$).
By rearranging Equation (3.2), the resistivity can be expressed as:

$$\rho = \frac{R \times A}{L}$$  \hspace{1cm} (3.3)

The electrical resistivity of any material is the resistance between the opposite faces of a unit cube of the material, Figure 3.1. Resistivity is an internal parameter of the material through which current is compelled to flow and describes how easily this material can transmit an electrical current. High values of resistivity imply that the material making up the wire is very resistant to the flow of electricity. Low values of resistivity show that the material making up the wire transmits electrical current very easily.
3.4. THEORETICAL DETERMINATION OF RESISTIVITY

The estimation of the apparent resistivity of the earth is relatively simple if several assumptions are made.

The first assumption is that a model-Earth is uniform and homogeneous, thus it possesses constant resistivity throughout the entire Earth.

The second assumption is that the Earth is a hemispherical resistor in a simple circuit consisting of a battery and two electrodes (the source and the sink electrodes) pounded into the ground, Figure 3.2. The battery generates direct electrical current that enters the Earth at the source electrode connected to the positive portal of the battery. The current exits at the sink electrode coupled to the negative portal of the battery.

![Figure 3.2. Current lines radiating from the source electrode and converging on the sink](Edwin S. Robinson, 1988)

When current is introduced to the ground, it is compelled to move outward from the source electrode. Due to the assumption that the Earth is homogeneous the current spreads outward in all directions from the electrode, and at each moment of time, the
current front will move through a hemispherical zone. The area of such a hemispherical zone can be found from the relationship:

\[ A = 2\pi \times d^2 \]  \hspace{1cm} (3.4)

where \( d \) is the distance from the source electrode to the point on the hemisphere surface defined by Equation (3.4), Figure 3.2.

By substituting equation (3.4) into equation (3.3), we can obtain an expression that defines resistance of the media at a point separated from the source by distance \( d \):

\[ R = \frac{\rho}{2\pi \times d} \]  \hspace{1cm} (3.5)

The potential difference resulting from the flow of current through the hemispherical resistor can be found from combining Ohm’s Law expressed by Equation (3.1) and Equation (3.5):

\[ V = \frac{I \times \rho}{2\pi \times d} = V_o - V_d \]

\hspace{1cm} (3.6)

where \( V_o \) is a potential at the source electrode;

\( V_d \) is a potential at the surface of the hemisphere with radius \( d \).

This equation demonstrates, that for any point located at the hemispherical surface with radius \( d \), the potential difference between this point and source electrode is the same. Such hemisphere is a surface of constant potential and is called an equipotential surface. In other words, the potential difference between a source and any point on the equipotential surface has the same numerical value.

When the two electrodes are a finite distance from each other, the potential at any point M separated by distance \( d_1 \) from the source electrode, and the distance \( d_2 \) from the sink electrode can be found as a sum of the potential contributions from source and sink electrodes for point M, Figure 18 (Edwin S Robinson, 1988):
\[ V = \frac{I \times \rho}{2\pi} \times \left( \frac{1}{d_1} - \frac{1}{d_2} \right) \]  

(3.7)

This equation can be employed to calculate the potential point by point throughout the earth. By plotting these points and connecting them the equipotential surfaces can be obtained (Figure 3.3).

Figure 3.3. Current lines and equipotential surfaces produced by the source and sink electrodes in a medium of uniform resistivity (Edwin S. Robinson, 1988)

3.5. APPARENT RESISTIVITY

To acquire 2-D electrical resistivity tomography data in the field, a four electrode array can be used. Two of these electrodes are used to inject electrical current into the ground and are referred to as current electrodes, Figure 3.4 (current electrodes are indicated by letters A and B). The other two electrodes are connected to a voltmeter and
are used to measure the potential difference between electrodes. These are called potential electrodes (Figure 3.4; potential electrodes are shown by letters N and M).

Figure 3.4. Current electrodes A and B and potential electrodes M and N. Current flow direction is shown by red lines and equipotential surfaces are indicated by blue lines.

The assumption that the media through which current is compelled to flow is homogeneous provides for a constant value of resistivity irrespective of where the voltmeter electrodes are placed.

Taking into account the geometry of electrodes configuration, illustrated in Figure 3.4, the electric potential at point M can be found from the Equation:

\[
V_M = \frac{I \times \rho}{2\pi} \times \left( \frac{1}{d_1} - \frac{1}{d_2} \right)
\]  

(3.8)
The potential at the N point can be calculated from the Equation:

\[
V_N = \frac{I \times \rho}{2\pi} \times \left( \frac{1}{d_3} - \frac{1}{d_4} \right)
\]  
(3.9)

Therefore, the potential gradient between these two points, \(V_{MN}\) is:

\[
V_{MN} = V_M - V_N = \frac{I \times \rho}{2\pi} \times \left( \frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4} \right)
\]  
(3.10)

In reality, the subsurface materials possess different physical characteristics, and the assumption that resistivity is the same everywhere is not reasonable. Thus, the resistivity value that is measured in the field is an average of resistivity values between two equipotential surfaces, and is known as the apparent resistivity \(\rho_a\). It can be expressed as:

\[
\rho_a = K \times \frac{V_{MN}}{I}
\]  
(3.11)

where \(K\) is the geometric factor that depends on the electrode array configuration:

\[
K = \frac{2\pi}{\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}}
\]  
(3.12)

3.6. ELECTRICAL RESISTIVITY CONFIGURATION

For modern electrical resistivity tomography surveys, multi-electrode systems are preferred. The greater number of electrodes permanently attached to multi-core cable increases investigation capabilities and saves time spent in the field. Use of multi-electrode systems allows combination vertical sounding/horizontal profiling data to be
acquired simultaneously. Also it allows the generation of a two-dimensional model of resistivity distribution (lateral and vertical).

For 2-D imaging using a modern multi-electrode system, the spacing between electrodes stays fixed for the entire survey. Measurements are taken sequentially using different sets of four electrodes controlled by switching device.

The depth of investigation is a function of an array type, the length of the array and the physical parameters of material underlying the area of interest, and typically ranges from one-third to one-fifth of the length of the entire array length (Robinson et al., 1988).

### 3.7. 2-D RESISTIVITY ARRAYS, WITH AN EMPHASIS ON DIPOLE-DIPOLE ARRAY

In this section, the more common electrode configurations such as Wenner array, Slumberger array, and Dipole-Dipole array are briefly discussed.

The geometry of an electrode array depends on the target depth, the time allowable for data acquisition, and the required spatial resolution.

When a multi-electrode system is used, the spacing between all electrodes stays stationary, while the distance between current and potential electrodes depends upon electrode configuration. This distance is controlled automatically by resistivity meter. The most electrical resistivity tomography surveying is done with one of the electrode geometries illustrated in Figure 3.5.

For the 2-D Wenner array (Figure 3.5), current and potential electrodes are separated by equal distance $a$:

$$AM = MN = NB = a$$  \hspace{1cm} (3.13)

All of electrodes are arranged along a continuous line, also known as a survey line or traverse. The geometric factor for Wenner Array is given by expression:

$$K_w = 2 \pi a$$  \hspace{1cm} (3.14)
1) Wenner Array

2) Schlumberger Array

3) Dipole-dipole Array

Figure 3.5. The most common electrode array configurations
For the 2-D Slumberger array (Figure 3.5), the current electrodes A and B are located on the opposite sides from center point of the array and both are separated by distance $l$. The passive electrodes N and M are placed between A and B electrodes and each of them are separated from the center by distance $b$.

The geometric factor for Slumberger array is given by expression:

$$K_S = \frac{\pi (L^2 - b^2)}{2b}$$  

(3.15)

The third geometry is attributed to the Dipole-Dipole configuration, where the potential electrodes M and N are not placed between the current electrodes A and B (Figure 3.5). The Dipole-Dipole array is logistically the most convenient in the field, especially for the large scale projects. In this array all four electrodes are placed along the same line, and the distance between the current electrodes A and B is equal to the distance between the potential electrodes M and N, represented by $a$:

$$AB = MN = a$$  

(3.16)

The distance between the middle points of current and the passive electrode sets is an integer multiple of $a$, and the factor itself is assigned to be equal to $n$ (Figure 3.5).

The geometrical factor $K$ can be found from the following expression:

$$K_{DD} = \pi * n(n^2 - 1) * a$$  

(3.17)

The Dipole-Dipole method was used in this research. This type of array has proven to be of the most efficiency in areas with great lateral variations in the depth to bedrock (W. Zhou, 1999).
4. SURVEY OBJECTIVE: RELATIVE TO DATA ACQUISITION

The objective of this study was to employ Electrical Resistivity Tomography (ERT) survey to delineate the depth to bedrock and to create a comprehensive geologic model that reflects the underground structure of the Route 60/65 study site. The main interest of MoDOT personnel was to delineate dissolution features, like air-filled voids and solution-widened joints that may compromise the long term serviceability of the planned intersection or create hazardous situations during construction works.

Two-dimensional multi-channel Electrical Resistivity Tomography is an effective tool used to image shallow subsurface (depth less than 100 ft / 30.48 m) in karst terrains. Resistivities of air-filled voids, clay-infilled cavities, dry soil, intensively weathered rock, and intact rock normally are significantly different (Table 3.1). Electrical current is compelled to flow through the ground primarily by electrolytic conduction. Factors such as porosity, conductivity, saturation, salinity, clay content, lithology, and temperature can affect the ability of different materials to conduct electrical current. Accordingly, materials of the same mineral content may exhibit different resistivity values. For instance, dry soil usually has much higher resistivity than saturated soil. The same situation appears with weathered and unweathered rock. Weathered rock is usually more porous and fractured, and it becomes more saturated with ground water. As a result, weathered rock has lower resistivity than an intact one.

According to studies (Anderson et al., 2006) conducted in southwestern Missouri, typical resistivity values for the subsurface materials are characterized as follows:

- Moist clays in Southwestern Missouri are normally characterized by low resistivity values usually less than 100 ohm-m, and may vary due to different degree of saturation, porosity, and layer thickness.
- Moist soils and intensively fractured rocks intermixed with clay are typically of resistivity values between 100 and 400 ohm-m. Such variation is explained by different porosity, saturation, clay content, and layer thickness.
- Relatively intact limestone with minimal clay content is characterized by higher resistivity values, typically more than 400 ohm-m, Resistivity values of intact
limestone may vary due to varying layer thickness, moisture content, porosity, saturation, and impurities.

- Air-filled cavities usually show very high resistivity values, usually more than 10000 ohm-m, but again, are variable depending on the conductivity of the surrounding strata and depth/size/shape of void. (Anderson et al., 2006)

Zones where relatively intact bedrock is surrounded by moist loose materials (such as clay), or zones where air-filled voids are embedded in relatively intact limestone, are zones of electrical resistivity contrast. These zones can be successfully detected by electrical resistivity tools.
5. ELECTRICAL RESISTIVITY DATA ACQUISITION

5.1. SITE DESCRIPTIONS: RELATIVE TO DATA ACQUISITION

The Route 60/65 study site, located in the Southeastern part of Springfield, Green County, Missouri, (Section 1.1) comprises the area immediately north of the existing highway 60, Figure 5.1.

The Route 60/65 study site is indicated by a white cross, as Figure 5.1 shows it is an open area with little vegetation and entirely covered by soil. Electrical Resistivity Tomography surveying was conducted during the second half of January when the ground was moist and frozen in places; with a temperature about 32 degree F.

Figure 5.1. Locality map showing the location of the Route 60/65 study site. White cross indicates area where electrical survey was performed
5.2. SURVEY DESIGN AND DATA ACQUISITION

Electrical Resistivity Tomography data was acquired along six traverses (Figure 5.2). Traverses were labeled with letters A, B, C, D, E, and F.

Figure 5.2. Survey layout. Location of highway 60 is indicated by the blue line

The closest to the highway traverse F was 40 ft / 12.2 m from the center line of highway 60 and the rest of traverses were separated from each other by 20 ft / 6 m intervals. All six traverses were aligned more-or-less parallel to the existing highway 60 (blue arrow roughly indicates the approximate location of the highway 60). MoDOT used its own system to describe location of borehole along the traverses. The Station 162+00 corresponds with the start point on the ERT traverse, and the Station 185+00 indicate the end of ERT traverse. The total length of each profile was approximately 2300 ft / 701.04 m. MoDOT used separation from the reference line (aligned with the center line of
highway 60) to indicate location of boreholes relative to the resistivity traverses. For example, Station 162+00, 40’ left, indicates borehole location, which coincides with the start point (mark 0 ft /0 m) on a resistivity traverse that is separated from the highway 60 center line by 40 ft /12.2 m (Figure 5.3).

ERT data was collected using the SuperSting Resistivity unit (Advanced Geosciences Inc.), Dipole-Dipole array configuration with 68 electrodes 5 ft /1.5 m apart. The Dipole-Dipole configuration is very sensitive to horizontal changes in resistivity (Zhou, 2007), which means that it performs well in the mapping of vertical structures such as vertically oriented dissolution-widened joints. This is well-suited for this survey. In addition, for large scale electrical resistivity surveys, the Dipole-Dipole array is logistically very convenient. A small electrode interval, such as 5 ft /1.5 m were chosen to ensure required depth of investigation and acceptable resolution.
5.3. EQUIPMENT USED FOR ELECTRICAL RESISTIVITY TOMOGRAPHY CONDUCTED IN THE ROUTE 60/65 STUDY

Electrical Resistivity Tomography (ERT) involves introduction of electrical current into the subsurface by means of electrodes attached to the ground. All required measurements are taken by resistivity meter.

The equipment used for this thesis setup is composed of the following components:

- A Multi-channel portable memory earth resistivity meter-SuperSting R8/IP, manufactured by Advanced Geosciences, Inc., (Figure 5.4). SuperSting R8/IP is usually powered by -12 volt battery. For larger scale projects, two batteries can be used.

![SuperSting Resistivity Imaging System](image)

Figure 5.4. Earth resistivity meter-SuperStingR8/IP, manufactured by Advanced Geosciences, Inc

- Sixty-eight electrodes connected to the insulated low resistance multi-core cable and the same amount of metal stakes. To facilitate propagation of charged
particles through subsurface materials, each electrode has to be attached to a metal stake that is plunged to the ground (Figure 5.4).

The setup scheme for a Dipole-Dipole array configuration is shown in Figure 5.5. Electrodes are attached to a multi-core cable along a straight line.

![Diagram of Dipole-Dipole array configuration](image)

**Figure 5.5.** Electrical resistivity Dipole–Dipole array configuration used in the field

The cable is connected to the switching unit hardwired into the SuperSting resistivity meter. This unit controls the selection of the current (A&B) and potential (M&N) electrodes for each measurement. The SuperSting resistivity meter is connected to a laptop computer where the data is stored.

### 5.4. ELECTRICAL RESISTIVITY TOMOGRAPHY DATA PROCESSING

The resistivity data sets collected in the field were converted into resistivity models, also known as ERT resistivity profiles, which were used for interpretation of subsurface conditions.
The RES2DINV software was used for processing of the data acquired in the Route 60/65 study site; (GEOTOMO SOFTWARE, Malaysia, copyright 1995-2006).

The following steps were involved into the ERT data processing:

- Inspection of the resistivity data sets for presence of unreasonable high and low (negative) resistivity values are also called “bad data points” (Loke, 2004).
- Removal of “bad data points”.
- Compilation of a resistivity model/ERT resistivity profile that displays horizontal and vertical resistivity distribution.

Before processing, ERT resistivity data acquired in the field had to be inspected for presence of “bad data points” (Loke, 2004). “Bad data points” mean resistivities of unrealistically high and low (negative) values. “Bad data points” can be caused by several reasons. One of them is a failure during the survey, such as electrode malfunctioning. Another reason is a very poor electrode-ground contact. “Bad” resistivity measurements may also be acquired when a metal stake attached to electrode is driven into an ice lens. Ice acts as an insulator, and affects measurements, which are taken at the electrode. Inspection of a “bad data points” can be done by viewing a profile plot, illustrated in Figure 5.6. The “bad data points” can appear as stand out points (in Figure 5.6, all “bad data points” are marked as red plus signs) (Loke, 2004). The RES2DINV software offers an option that allows for removal of such points manually by simply clicking on them.

In this thesis, quality control for the presence of unrealistically high and low (negative) resistivity values was performed. During ERT data acquisition, the ground was frozen at several locations, and that slightly affected the resistivity measurements. After all resistivity data sets were examined, a few “bad data points” were detected and removed.

After the resistivity data sets acquired in the field were inspected and all unrealistic values were removed, the RES2DINV software used an inversion algorithm to convert the measured resistivity data sets into resistivity model/ERT resistivity profiles, which reflect lateral and vertical resistivity distribution.

The software creates a resistivity model/resistivity profile that has the same resistivity distribution as actual resistivity distribution below corresponding traverse. To increase the quality of the calculated model, the Root Mean Square (RMS) value is used
(Loke, 2004). The smaller this value, the better the calculated model correlates with real resistivity distribution. Usually, the RMS value, up to 5%, provides a good quality control of the calculated model.

To create a resistivity model, the RES2DINV subdivides the subsurface into a finite number of rectangular pixels (Figure 5.7). Each pixel is assigned a resistivity value which represents the resistivity of different materials encompassed within that discrete pixel; therefore some lateral and vertical smoothing takes place (Anderson, 2006).

The size of the pixels is affected by the spacing between adjacent electrodes. Horizontal dimension of a pixel is equal to lateral distance between adjacent electrodes, the and at shallow depth the vertical dimension is approximately equal to 20% of the spacing between two adjacent electrodes. With increasing depth of investigation, vertical dimension of pixels gradually increases up to 100% of the distance between adjacent
electrodes (Anderson et al., 2006). The resolution of the output model is a function of the pixel size. Thus, with increasing depth of investigation, resolution decreases.

**Figure 5.7.** Arrangement of the blocks used in a model together with the data points in the pseudo section (the pixel size increases with depth)

When a Dipole-Dipole array is used, the maximum depth of investigation is approximately 20% - 25% of the array length and is affected by subsurface conditions. For this project, the maximum investigation depth is about 70 ft / 21 m.

### 5.5. Resolution Limitations of Electrical Resistivity Tomography Method

The resolution of ERT resistivity profile defines the accuracy of interpretation of subsurface conditions. Resolution is a function of electrode spacing, and resistivity contrast between lithologically different earth materials (Section 3.1.2).
The size of a pixel is a main estimate of ERT imaging resolution (Section 5.4). In this thesis at the shallow depth, the width of the pixel is about 5 ft / 1.5 m and the vertical dimension of the pixel is around 1 ft / 0.3 m. It means that, at the shallow depth all objects that are less than the size of the pixel will be easily detected. With increasing depth the vertical dimension of the pixels becomes greater and that affects ERT resolution (Section 5.4). To estimate the size of all detectable objects at a certain depth, it is recommended to compile a synthetic resistivity model. The model can allows visually estimate the size of the pixels at different depth layers.

During ERT survey to induce current to flow through deeper layers the distance between current and potential electrodes is gradually increased. That affects the sensitivity of the ERT method. Gradually increasing distance between electrodes lowers the intensity of current flow, and accordingly the sensitivity of ERT survey. Thus, interpretation of a smaller scale objects at a greater depth becomes increasingly difficult and sometimes small objects can be misinterpreted.

Another parameter that defines resolution of ERT resistivity profile is the resistivity contrast. When lithologically different materials exhibit similar conductivity parameters sometimes it is difficult to differentiate them on the basis of their resistivity parameters. For example, both intact bedrock and air-filled voids typically are characterized by high resistivity values. When air-filled void is embedded into intact limestone, it typically can not be easily detected on resistivity profile because of low resistivity contrast. To increase reliability of interpretations based on analysis of ERT resistivity profiles, areas with questionable subsurface conditions should be tested by other complimentary methods. Due to the limitations of Electrical Resistivity Tomography method, the resistivity profiles should be interpreted with caution.
6. DATA INTERPRETATION

MoDOT’s objectives were to delineate depth of bedrock and inspect the Route 60/65 study site for the presence of solution-associated features such as air-filled cavities and dissolution-widened joints.

The ERT resistivity profiles (resistivity models) were used for interpretation of subsurface condition within the study site (Figures 6.1-6.7).

MoDOT conducted geotechnical ground sampling in the study site; 49 boreholes were drilled more-or-less along resistivity traverses (Section 7). Information on the type of overburden (clay with chert fragments) and bedrock composition (limestone) was obtained. The depth to bedrock at the drilling location also was determined. This data was compared with six resistivity models (Figures 6.1-6.7) to define the clay/limestone boundary.

The best correlation between the resistivity contour value and the borehole-depth to bedrock was established at a resistivity value of 85 ohm-m. The reddish brown clay with admixed chert fragments overburden was characterized by resistivity values of less than 85 ohm-m, and the intact limestone was correlated with 400 ohm-m resistivity contour values and higher. Frozen soil was characterized by resistivity values above 1000 ohm-m. Further observation of resistivity profiles yielded the following conclusions:

6.1. BEDROCK TOPOGRAPHY

Bedrock on the resistivity profiles appears to have an irregular upper interface, and features such as pinnacles and cutters can be observed. A map of the bedrock topography was compiled (Figure 6.8). The depth of bedrock also was calculated and six vertical profiles were compiled (Figures 6.9 and 6.10). Each of these vertical profiles indicates the depth to bedrock (red line) relative to the surface elevation (blue line) in the Route 60/65 study site. The shallowest bedrock was interpreted to be found at a few feet from the ground surface (Traverse F, Figure 6.6), and according to our interpretations, the deepest bedrock was interpreted to be found at the depth up to 41 ft /12.5 m. (Traverse A, Figure 6.1).
Figure 6.1. Uninterpreted and interpreted versions of resistivity profile A. The top of bedrock (black line) correlates reasonably well with the 85ohm-m contour interval. Borehole locations have been superposed in red. Distance 0 ft on the resistivity profile corresponds with highway 60 Station 162+00; Distance 2300 ft corresponds with Station 185+00.
Figure 6.2. Uninterpreted and interpreted versions of resistivity profile B. The top of bedrock (black line) correlates reasonably well with the 85ohm-m contour interval. Borehole locations have been superposed in red. Distance 0 ft on the resistivity profile corresponds with highway 60 Station 162+00; Distance 2300 ft corresponds with Station 185+00.
Figure 6.3. Uninterpreted and interpreted versions of resistivity profile C. The top of bedrock (black line) correlates reasonably well with the 85ohm-m contour interval. Borehole locations have been superposed in red. Distance 0 ft on the resistivity profile corresponds with highway 60 Station 162+00; Distance 2300 ft corresponds with Station 185+00.
Figure 6.4. Uninterpreted and interpreted versions of resistivity profile D. The top of bedrock (black line) correlates reasonably well with the 85ohm-m contour interval. Borehole locations have been superposed in red. Distance 0 ft on the resistivity profile corresponds with highway 60 Station 162+00; Distance 2300 ft corresponds with Station 185+00
Figure 6.5. Uninterpreted and interpreted versions of resistivity profile E. The top of bedrock (black line) correlates reasonably well with the 85ohm-m contour interval. Borehole locations have been superposed in red. Distance 0 ft on the resistivity profile corresponds with highway 60 Station 162+00; Distance 2300 ft corresponds with Station 185+00.
Figure 6.6. Uninterpreted and interpreted versions of resistivity profile F. The top of bedrock (black line) correlates reasonably well with the 85ohm-m contour interval. Borehole locations have been superposed in red. Distance 0 ft on the resistivity profile corresponds with highway 60 Station 162+00; Distance 2300 ft corresponds with Station 185+00.
Figure 6.7. Resistivity profiles are arranged in the same sequence as in the Route 60/65 study site.
According to MoDOT’s borehole control, weathered limestone was found at several locations. The maximum estimated thickness of the weathering zone is about 5 ft /1.5 m. Interpretation of the resistivity profiles suggests some variations in the thickness of the weathering/transition zone. The thickness varies from several feet (Traverse B, Figure 6.3) to about 30 ft /9 m (Traverse F, Figure 6.6). The transition zone is indicated by resistivity contour intervals from 85 ohm-m to 400 ohm-m. On the left side of all six resistivity profiles, the clay/limestone transition zone appears to be thicker and laterally more-or-less evenly distributed. Toward the right side of the resistivity profiles, it thins down to a few feet. Presence of a transition zone suggests that the bedrock surface is fractured and more porous. Fractures and interconnected pores permit clay particles and moisture, which increases electrical conductivity and lowers resistivity values.
6.2. JOINTS

The resistivity profiles were examined for the presence of dissolution-widened joints and fractures. The only difference between joints and fractures is their lateral extension. Joints exhibit continuous pattern over larger distance. The most prominent joint was observed at all six resistivity traverses (reference location: Traverse A-1760 ft /536.4 m from the start point) (Figure 6.1). The feature was interpreted as a solution-widened joint with clay-infill that appears to have ENE strike direction. Borehole control correlates well with this interpretation. The ground was sampled at Station 178+00, 150 left (Section 7). Further in this thesis, this feature is referred to as joint I.

Another, approximately 120 ft /36.6 m, feature southeast (to the right) of joint I, also was interpreted as a dissolution-widened joint (Traverse A-1920 ft /582.5 m from the start point). This feature can be observed at all six resistivity profiles (Figure 6.7). The resistivity profile for the Traverse A, (Figure 6.1) shows a narrow, vertically elongated zone of low resistivity that was interpreted as a clay-infilled joint. Borehole control at that location was terminated at a depth of 41.4 ft / 12.5 m in moderately hard rock (Station 181+00,100’ left). Presumably, the auger refusal was caused by the flank of dissolution-widened joint. This feature is referred to as joint II.

6.3. FRACTURES

Several vertically oriented features of low resistivity were interpreted as solution-widened fractures. Interpreted fractures were identified at the following locations (all locations are given relative to the beginning of a corresponding traverse):

Traverse A: 440 ft /134.1 m; 580 ft /176.8 m; 840 ft /256 m; 1020 ft /310.9 m; 1220 ft /371.9 m; 1440 ft /438.9 m; 2260 ft /689 m;
Traverse B: 220 ft /67 m; 580 ft /176.8 m; 920 ft /280.4 m; 1080 ft /329 m; 2240 ft /682.7
Traverse C: 1060 ft /323 m; 2260 ft /689 m;
Traverse D: 940 ft /201 m; 1180 ft / 359.6 m;
Traverse E: 800 ft /244 m; 920 ft /280.4 m; 1140 ft /347.5 m; 1360 ft /414.5 m; 1440 ft /438.9 m; 2060 ft /627.9 m;
Traverse F: 920 ft /280.4 m; 1080 ft /329.2 m; 1160 ft /353.6 m; 1260 ft /384 m;
1460 ft /445 m; 2060 ft /628 m;

A map of the bedrock topography was compiled (Figure 6.8). Joints and several prominent fractures were superimposed on the bedrock map. That helps to visualize the strike orientation of solution widened discontinuities. The information used for compilation of the bedrock topography map is based on resistivity values and features interpreted as solution-widened joints, and the fractures appeared wider than they are supposed to be in reality. On this map, the solution-affected features (joints and fractures) are almost orthogonal with general NW- and ENE-trending, which correlates well with the strike orientation, measured in Sequiota Park (Section 1.4.2).

6.4. AIR-FILLED CAVITIES

Visual inspection of the resistivity profiles revealed several high-resistivity zones (higher than 5000 ohm-m, Figures 6.2-6.7). These zones are not interpreted as air-filled cavities due to the following reasons:

The shape of the high resistivity zones suggests that this is the smooth resistivity transition from saturated at the surface limestone to more indurated and dry interior of intact limestone. Electrical current can not easily propagate through dry interior of limestone and that affects resistivity parameters.

An air-filled cavity can appear when these geological conditions are present: the system of fractures or dissolution-widened joint has to be connected to the air-filled cavity (Section 2). Presence of fractures or joints will lower resistivity values of the surrounding media. According to the resistivity profiles, none of the high-resistivity zones are directly connected to a low-resistivity zone. Thus, air-filled cavities are not present beneath the Route 60/65 study site.

To assure reliability of interpretations, the borehole control data were superimposed on the resistivity profiles (Figures 6.2-6.7). In general, borehole-depth of bedrock correlates well with the resistivity-depth to bedrock interpretations, except where the boreholes are presumed to have terminated due to the following reasons:
The borehole was terminated in shallow limestone lenses and/or boulders that do not actually constitute the top-of-the-rock (Traverse A: 1300 ft / 396.2 m (Figure 6.1); Station: 175+00; 100’ left, Section 7).

In areas of vertically oriented joints infilled with moist clay, where the auger hit jagged flank of the fracture (Traverse A- 1120 ft / 341.4 m; Station: 173+20; 100’ left, Section 7).

Another explanation for the data inconsistency is that the solution-widened joint infilled by moist clay was slightly shifted from the actual location of the boring location (Traverse A- 1800 ft / 548.6 m; Station: 180+00; 110’ left, Section 7).

All resistivity profiles exhibit higher resistivity values closer to the ground surface. That anomaly can be explained by the fact that the ground was frozen during the resistivity data acquisition. Ice acts as an insulator, and the electrical conductivity of frozen soil was lower at the time of the ERT survey. Conductivity is the reciprocal of resistivity, thus, resistivity of the soil at that moment of time was higher than was expected.

The thickness of overburden was calculated and six profiles showing soil thickness distribution were compiled (Figures 6.9 and 6.10). These profiles allow visual estimation of the bedrock topography.

All interpretations were prepared within the limitations of Electrical Resistivity Method stated in Section 5.5.
The elevation of the bedrock for traverse A:

The elevation of the bedrock for traverse B:

The elevation of the bedrock for traverse C:

Figure 6.9. Soil thickness distribution along traverses A, B, and C (Blue line indicates land surface, red line indicates bedrock elevation)
The elevation of the bedrock for traverse D:

The elevation of the bedrock for traverse E:

The elevation of the bedrock for traverse F:

Figure 6.10. Soil thickness distribution along traverses D, E, and F (Blue line indicates land surface, red line indicates bedrock elevation)
7. BOREHOLE DATA ACQUIRED FOR THE ROUTE I 60/65 STUDY SITE

The Missouri Department of Transportation conducted geotechnical investigation for the Route 60/65 study site; thirty-seven exploratory boreholes were drilled prior to commencement of ERT survey, and twelve more boreholes were drilled after geophysical interpretations were prepared. The data obtained from borehole control and ERT depth interpretations are given in the Table 7.1. According to the borehole control, the overburden is comprised of reddish brown residual clay with interspersed chert fragments. Bedrock is a medium to coarse-grained gray limestone, thin to medium bedded. The bedrock composition proves that the bedrock in the Route 60/65 study site is Burlington-Keokuk Limestone.

Table 7.1. Bedrock surface elevation from electrical resistivity pseudo sections and borings

<table>
<thead>
<tr>
<th>Borehole Location (station and offset)</th>
<th>Borehole depth to bedrock (feet)</th>
<th>Resistivity profile &amp; location (feet)</th>
<th>Resistivity depth to bedrock (feet)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>162+00; 100’ left</td>
<td>26.4</td>
<td>A; 0</td>
<td>?</td>
<td>Not imaged on resistivity profile</td>
</tr>
<tr>
<td>164+65; 100’ left</td>
<td>31.6</td>
<td>A; 265</td>
<td>31.2</td>
<td></td>
</tr>
<tr>
<td>164+90; 95’ left</td>
<td>13.8</td>
<td>A; 290</td>
<td>~15</td>
<td>Between traverses D and A.</td>
</tr>
<tr>
<td>169+80; 60’ left</td>
<td>16.2</td>
<td>E; 780</td>
<td>16.1</td>
<td></td>
</tr>
<tr>
<td>170+00; 100’ left</td>
<td>22.9</td>
<td>A; 800</td>
<td>23.1</td>
<td></td>
</tr>
<tr>
<td>171+00; 40’ left</td>
<td>11.8</td>
<td>F; 900</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>172+00; 100’ left</td>
<td>11.7</td>
<td>A; 1000</td>
<td>11.3</td>
<td></td>
</tr>
<tr>
<td>172+90; 40’ left</td>
<td>16.1</td>
<td>F; 1090</td>
<td>~12.5</td>
<td>Flank of fracture</td>
</tr>
<tr>
<td>173+05; 100’ left</td>
<td>21.2</td>
<td>A; 1105</td>
<td>20.5</td>
<td></td>
</tr>
<tr>
<td>173+20; 60’ left</td>
<td>17.5</td>
<td>E; 1120</td>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td>173+20; 100’ left</td>
<td>31.8</td>
<td>A; 1120</td>
<td>21.5</td>
<td>Flank of fracture</td>
</tr>
</tbody>
</table>
Table 7.1. (continued) Bedrock surface elevation from electrical resistivity pseudo sections and borings

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation</th>
<th>Zone</th>
<th>TD</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>173+60; 80’ left</td>
<td>18.2</td>
<td>D</td>
<td>1160</td>
<td>18.5</td>
</tr>
<tr>
<td>174+00; 100’ left</td>
<td>23.0</td>
<td>A</td>
<td>1200</td>
<td>23.1</td>
</tr>
<tr>
<td>174+50; 100’ left</td>
<td>22.6</td>
<td>A</td>
<td>1250</td>
<td>22</td>
</tr>
<tr>
<td>174+90; 40’ left</td>
<td>12.4</td>
<td>F</td>
<td>1290</td>
<td>12.4</td>
</tr>
<tr>
<td>175+00; 100’ left</td>
<td>8.5</td>
<td>A</td>
<td>1300</td>
<td>16.4</td>
</tr>
<tr>
<td>Appears to have intersected a limestone lens or boulder – not bedrock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>175+00; 90 left</td>
<td>16.7</td>
<td>A</td>
<td>1300</td>
<td>16.4</td>
</tr>
<tr>
<td>175+50; 100’ left</td>
<td>?</td>
<td>A</td>
<td>1350</td>
<td>19.75</td>
</tr>
<tr>
<td>Borehole TD at 20.2’</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>176+00; 100’ left</td>
<td>15.4</td>
<td>A</td>
<td>1400</td>
<td>16.4</td>
</tr>
<tr>
<td>176+00; 110’ left</td>
<td>22.0</td>
<td>A</td>
<td>1400</td>
<td>~23.0</td>
</tr>
<tr>
<td>BH is off traverse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>176+00; 120’ left</td>
<td>24.1</td>
<td>B</td>
<td>1400</td>
<td>26</td>
</tr>
<tr>
<td>176+00; 150 left</td>
<td>27.9</td>
<td>C</td>
<td>1400</td>
<td>27.5</td>
</tr>
<tr>
<td>176+40; 100’ left</td>
<td>25.1</td>
<td>A</td>
<td>1440</td>
<td>23.1</td>
</tr>
<tr>
<td>Flank of fracture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>176+50; 100’ left</td>
<td>22.4</td>
<td>A</td>
<td>1450</td>
<td>21</td>
</tr>
<tr>
<td>Flank of fracture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>177+00; 100’ left</td>
<td>35.6</td>
<td>A</td>
<td>1500</td>
<td>31.2</td>
</tr>
<tr>
<td>Flank of fracture</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>177+75; 100’ left</td>
<td>12.1</td>
<td>A</td>
<td>1575</td>
<td>12</td>
</tr>
<tr>
<td>178+00; 85’ left</td>
<td>20</td>
<td>D</td>
<td>1600</td>
<td>16.7</td>
</tr>
<tr>
<td>Between traverses D and A.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>178+00; 100’ left</td>
<td>11.3</td>
<td>A</td>
<td>1600</td>
<td>11</td>
</tr>
<tr>
<td>178+00; 120’ left</td>
<td>17.2</td>
<td>B</td>
<td>1600</td>
<td>17.5</td>
</tr>
<tr>
<td>BH did not encounter bedrock</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>178+00; 150’ left</td>
<td>&gt;36.0</td>
<td>C</td>
<td>1600</td>
<td>27</td>
</tr>
<tr>
<td>BH is off-line</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>179+00; 100’ left</td>
<td>7.5(boulder)</td>
<td>A</td>
<td>1700</td>
<td>28.5</td>
</tr>
<tr>
<td>Borehole encountered boulder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>179+00; 100’ left</td>
<td>31</td>
<td>A</td>
<td>1700</td>
<td></td>
</tr>
<tr>
<td>179+00; 110’ left</td>
<td>29.9</td>
<td>A</td>
<td>1700</td>
<td>~28</td>
</tr>
<tr>
<td>Between traverses A and B. Ties both well</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>179+00; 110’ left</td>
<td>29.9</td>
<td>B</td>
<td>1700</td>
<td>~28</td>
</tr>
<tr>
<td>179+20; 40’ left</td>
<td>7.4</td>
<td>F</td>
<td>1720</td>
<td>7</td>
</tr>
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Table 7.1. (continued) Bedrock surface elevation from electrical resistivity pseudo sections and borings

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation</th>
<th>Layer</th>
<th>Date</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>179+40; 80’ left</td>
<td>20.2</td>
<td>D</td>
<td>1740</td>
<td>20.1</td>
</tr>
<tr>
<td>179+60; 100’ left</td>
<td>29.5</td>
<td>A</td>
<td>1760</td>
<td>29</td>
</tr>
<tr>
<td>180+00; 100’ left</td>
<td>13.4</td>
<td>A</td>
<td>1800</td>
<td>13.76</td>
</tr>
<tr>
<td>180+00; 110’ left</td>
<td>12.5</td>
<td>A</td>
<td>1800</td>
<td>~10 Between traverses A and B. Ties A better</td>
</tr>
<tr>
<td>180+00; 110’ left</td>
<td>12.5</td>
<td>B</td>
<td>1800</td>
<td>6</td>
</tr>
<tr>
<td>180+00; 150’ left</td>
<td>4.5</td>
<td>C</td>
<td>1800</td>
<td>4.7</td>
</tr>
<tr>
<td>180+50; 100’ left</td>
<td>11.9</td>
<td>A</td>
<td>1850</td>
<td>11.3</td>
</tr>
<tr>
<td>181+00; 100’ left</td>
<td>41.4</td>
<td>A</td>
<td>1900</td>
<td>27.5 Flank of fracture</td>
</tr>
<tr>
<td>182+00; 80’ left</td>
<td>6.4</td>
<td>D</td>
<td>2000</td>
<td>6.5</td>
</tr>
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<td>8.7</td>
<td>A</td>
<td>2000</td>
<td>8.5</td>
</tr>
<tr>
<td>182+00; 150’ left</td>
<td>6.5</td>
<td>C</td>
<td>2000</td>
<td>6.4</td>
</tr>
<tr>
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<td>9.3</td>
<td>C</td>
<td>2010</td>
<td>9</td>
</tr>
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<td>18.3</td>
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<td>2100</td>
<td>11.3 Flank of fracture, Horizontal smoothing</td>
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<td>A</td>
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</table>
8. CONCLUSIONS

Electrical Resistivity Tomography survey was conducted in the Route 60/65 study site to delineate depth to bedrock and locate solution-widened joints/fractures and air-filled cavities if there are present. Borehole control was also available, and was used as reference information to correlate the resistivity values with the clayey overburden, bedrock/overburden interface and intact limestone.

According to the results obtained during the Electrical Resistivity Tomography data analysis, the following conclusions were made:

- The Route 60/65 study site is underlined by intensively weathered Burlington-Keokuk Limestone. The dissolution process has resulted in formation of solution-widened clay-infilled joints and fractures. Bedrock upper interface can be characterized by presence of closely spaced pinnacles and cutters. Due to varying bedrock elevation the thickness of overburden is also variable, it can be as thin as a few inches an as thick as 41.4 ft /12.6 m (Figures 6.9 and 6.10, Table 7.1).
- Thickness of overburden along the Route 60/65 study site is highly variable, thus under the load of the planned intersection, the differential settlement can occur.
- Two ENE oriented features were interpreted as dissolution widened joints (Joint I & Joint II), and several solution-widened fractures were located along all six resistivity profiles (Section 6). All above stated features were interpreted as solution-widened and infiltrated with clay and other fine-grained low-resistivity sediment. The joints and fractures within the Route 60/65 study site are nearly orthogonal and exhibit NE and NW trending (Figure 5.1) which correlates well with the general attitude of the joints and fractures in Greene County (Section 1.3.2.).
- Air-filled cavities were not found within the Route 60/65 study site.

Electrical Resistivity Tomography provides the resistivity profiles that can be used for interpretations of subsurface conditions. Borehole data can be used as reference information and as a quality control. According to the results of this study, implementation of Electrical Resistivity Tomography, as a complementary tool, for site characterization provides significantly better results than borehole control alone. It is
recommended to conduct preliminary geotechnical ground sampling to provide ERT interpretations with reference information, such as depth to bedrock at a few locations and information about earth materials such as composition of overburden and bedrock. When ERT resistivity profiles are constrained with ground truth the interpretations of subsurface conditions are of sufficiently good quality.

This geophysical investigation demonstrates that the combination of conventional geotechnical engineering with engineering geophysics yields the best results for the site characterization projects, especially in geologically complex areas.
BIBLIOGRAPHY


Iana Muchaidze was born in Tbilisi, Georgia on June 22, 1976. In December 1998, she received her BSc. in Structural Engineering from Georgian Technical University in Tbilisi, Georgia. Right after that she started working in a military organization “Delta”, Tbilisi, Georgia. In August 2008, she received her M.S. in Geological Engineering from Missouri University of Science and Technology.