ELECTRICAL IMAGING:
A Method for Identifying Potential Collapse and other Karst Features Near Roadways

By

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Abstract

Electrical Imaging (EI) is a geophysical method developed over the past several years that provides a two or three dimensional resistivity model of the subsurface. EI can provide information about distinct subsurface boundaries and conditions, which can indicate soil or bedrock lithology variations. In particular, EI can be very effective in characterizing potential collapse features associated with sinkhole activity. Frequently, in karst systems, boreholes drilled without regard to the variability of karst geology do not intersect areas of interest, such as developing collapse features in the subsurface. Poor location of borings can result in inadequate subsurface data, and could misrepresent the subsurface system leading to additional costs for remedial design or additional investigation of developing sinkholes.

In the past, electrical resistivity techniques performed by experienced geophysicists had proven to be effective tools for characterizing the subsurface but certain limitations caused theses techniques to be utilized less within the last two decades. These limitations were the following: 1) the technique was very labor intensive, a resistivity crew could range from three to five people. 2) interpretation of the data was time-intensive, and methods differed as to ways of obtaining accurate subsurface representations. Recently, the development of computer-controlled multi-electrode resistivity survey systems and the development of resistivity inversion modeling software have allowed for more cost-effective EI surveys and better representation of the subsurface. With these two factors improved, electrical resistivity is starting to be employed more often. New advances in EI have allowed for three-dimensional surveys and cross-borehole surveys which will make this technique even more successful for sinkhole and fracture characterization in complex systems.

Introduction

Sinkholes are often a major development hazard in areas underlain by carbonate rocks. Road and highway subsidence, building foundation collapse, and dam leakage are a few of the problems associated with sinkholes. Structural instability associated with sinkholes can occur as a sudden collapse of the ground surface or as a less catastrophic, but recurring drainage problem. Within karst regions, either scenario can be expensive to design and implement controls for present and future structures. Frequently, borings drilled within karst regions do not intersect areas of concern in the subsurface. Misplaced borings can provide inadequate subsurface data, and could misrepresent the subsurface system leading to additional costs for remedial design or additional investigation. Rapid reconnaissance surveys using remote sensing (e.g. Aerial Photograph Evaluation) and surface geophysical techniques integrated with a boring plan are best used to aid in the proper location of test borings to identify subsurface features related to karst development.

Electrical resistivity techniques have been utilized successfully for characterizing the subsurface for many years (Roman, 1951). Certain limitations of this technique have caused resistivity to be utilized less over recent years. These limitations are: 1) The technique was very labor intensive. A resistivity crew could range from three to five people. 2) Interpretation of the data was time-intensive, and methods differed as to ways of obtaining accurate subsurface representations. These methods have limitations because they are largely based upon individual subjective interpretation.

The development of computer-controlled multi-electrode resistivity survey systems and the development of resistivity inversion modeling software (Loke and Barker, 1996) have allowed for more cost-effective resistivity surveys and better representation of the subsurface. These surveys are typically referred to as Electrical Imaging (EI) surveys. Most EI surveys are collected as two-dimensional surveys. The inversion modeling software also processes three-dimensional surveys. These factors allow data to be collected and processed quickly, within a few hours, and as a result EI is becoming a more valuable tool in subsurface investigations.

Electrical Resistivity Methods

EI surveys are typically conducted to determine the resistivity of the subsurface. Resistivity data can be used to determine the location of variations in geologic and soil strata, soil/bedrock interface topography, bedrock fractures, faults, and voids. The method has been used effectively to delineate old waste sites and landfill boundaries and to map hydrogeologic and mineral resource boundaries.

Resistivity values are found for earth materials to cover a wide range. This variety of resistivities is what makes resistivity surveying a viable technique for many applications. Table 1 describes typical resistivities of earth materials.

Table 1: Typical Electrical Resistivities of Earth Materials

Material	Resistivity (ohmmeter)
Clay	1-60
Sand, Wet to Moist	20-200
Shale	1-500
Sandstone	150-450
Porous Limestone	100-1,000
Dense Limestone	1,000-1,000,000
Metamorphic Rocks	50-1,000,000
Igneous Rocks	100-1,000,000

Fundamental to all resistivity methods is the concept that current (I) can be impressed into the ground and the effects of this current within the ground can be measured. The effect of potential (V) or differences of potential, ratio of potential differences, or some other parameter that is directly related to these variables is the commonly measured effect of the impressed current. The principal differences among various methods of EI lie in the number and spacing of the current and potential electrodes, the variable quantity determined, and the manner of presenting the results.

In application, a series of measurements is made between a variety of current electrode pairs and potential electrode pairs. In general, as the distance between the two electrodes increase, the apparent resistivity p_a is measured at greater depths and across increasing volumes of ground as shown in Figure 1.

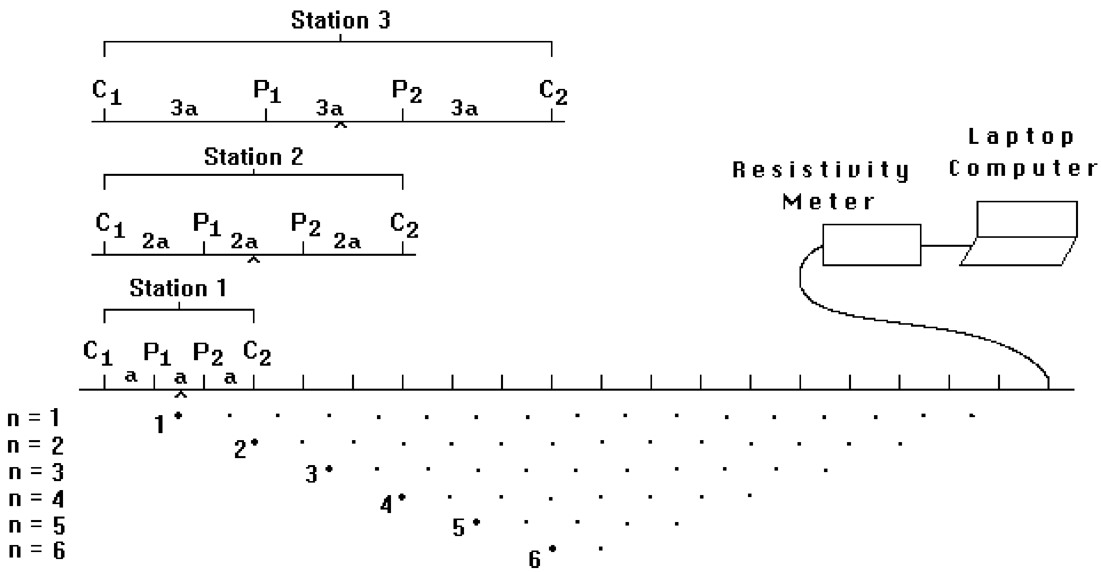

Figure 1 – Example of data measurement locations for 2D surveys (from AGI, Inc, 1999).

EI Data Collection

For EI data collection, SAIC uses a Sting/Swift multielectrode system manufactured by Advanced Geosciences, Inc. (AGI) of Austin, Texas. The EI equipment is composed of three primary components: 1) the Sting R1 resistivity meter with data storage capability; 2) the Swift automatic multielectrode switching system, which is an accessory for the Sting; and 3) the Sting/Swift cables which contain fixed cylindrical stainless steel switches that attach to stainless steel electrodes placed into the ground.

2D Data Collection

The EI system automatically energizes different electrodes to measure apparent resistivities at new horizontal locations and depths. Commonly, a series of 28 to 112 stainless steel electrodes are driven 6 to 12 inches into the ground at a fixed interval to establish earth contact. At most sites, the interval is established to be from 1 to 10 meters. Although the system can be programmed to use any electrode arrangement, the data are collected typically in a dipole-dipole electrode arrangement. The dipole-dipole arrangement provides increased resolution over other electrode array configurations. In the dipole-dipole arrangement, two electrodes are used to provide current to the subsurface, while two other electrodes some distance away are used to measure the voltage. The current and voltage electrodes do not overlay each other as in other electrode arrangements.

During preparation for data collection, the operator programs the Sting for the chosen number of current pairs (in electrode spacing measurements) to energize and the maximum separation (in electrode spacing measurements) to measure the potentials. These two numbers determine the total number of measurement to be collected along the electrode spread and the total depth of investigation. The Sting digitally records this information for use in data processing and quality assurance. The 2-D model assumes that all structures are infinitely long and perpendicular to the EI survey line. Because not all structures can be characterized in this manner and can be considerably more complex, 3-D surveys can be conducted.

3D Data Collection

As stated above, to compensate for subsurface complexity 3-D data can be collected. The amount of current, potential, and the configuration of electrodes are analyzed to yield an apparent resistivity value between electrodes. The electrodes for such a survey are arranged in a rectangular grid (Figure 2). The EI system automatically energizes different electrodes to measure apparent resistivities at new horizontal locations and depths. The EI system can be used to determine a three-dimensional (3-D) resistivity model for the subsurface using the data obtained from a 3-D electrical imaging E-SCAN type of survey (Li and Oldenburg 1992).

As with a 2-D survey, the operator programs the Sting for the chosen number of current pairs (in electrode spacing measurements) to energize and the maximum separation (in electrode spacing measurements) to measure the potentials. These two numbers determine the total number of measurement to be collected along the electrode spread and the total depth of investigation. The Sting digitally records this information for use in data processing and quality assurance.

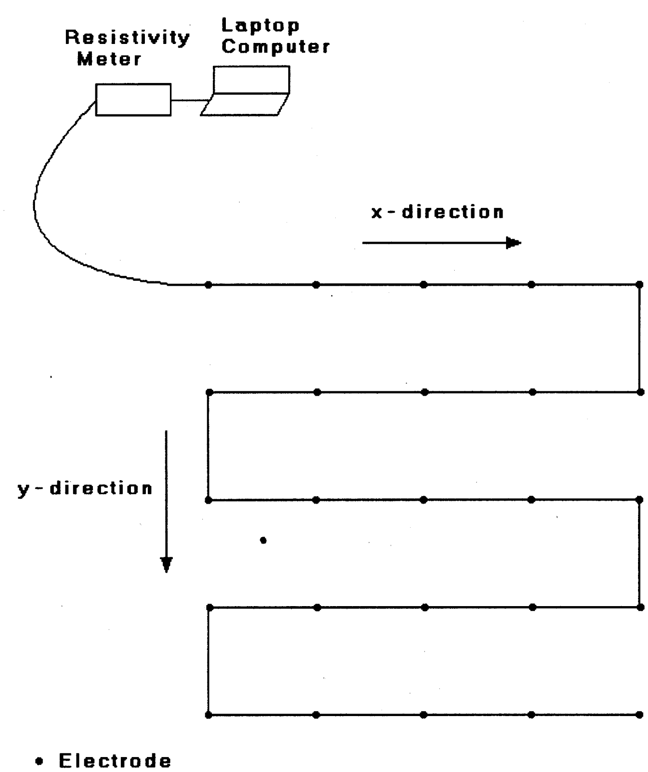

Figure 2. A schematic diagram for one possible layout for a 3D survey (Loke, 1997).

The most commonly used electrode configuration for 3D surveys is the pole-pole array. As presented in Figure 3, each electrode is used as a current electrode and the potentials at all the other electrodes are measured It can be very time-consuming to make such a large number of measurements with typical single-channel resistivity meters commonly used for 2D surveys. For large survey grids, it is common to limit the maximum spacing used in the measurements to about 8 to 10 times the minimum electrode spacing. To map large areas with a limited number of electrodes in a multi-electrode resistivity meter system, the roll-along technique can be used (Dahlin and Bernstone, 1997)

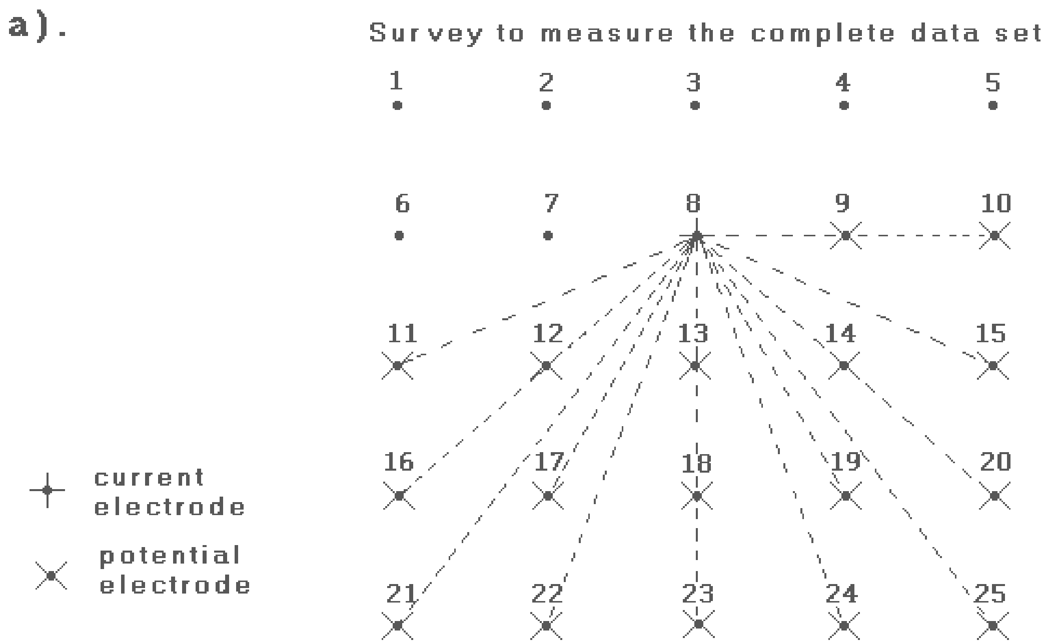

Figure 3. The location of potential electrodes corresponding to a single current electrode in the arrangement used by a survey to measure the complete data set (Loke, 1997).

Data Modeling and Interpretation

The apparent resistivity p_a, as measured by the EI system, is the product of a large area of the subsurface responding to the impressed current. Interpretation of apparent resistivity data collected in the field without reduction provides a qualitative product very similar to many electromagnetic (EM) methods. Because the earth is not homogeneous, it is useful to model the resistivities at discrete locations in order to make a more quantified interpretation. Inverse modeling of the data is performed using RES2DINV/RES3DINV™ (Loke, 1997) to produce a three-dimensional resistivity model based on the apparent resistivity data.

Final data processing involves the generation of color-enhanced contour maps of the data using a two-dimensional mapping program. EI resistivity models are presented in cross-section or 3D model blocks, with inline distance shown along the horizontal axis, depths, or elevation along the vertical axis. The geoelectrical model presents the electrical stratigraphy (electrostratigraphy) of the subsurface.

Following the data collection and inversion modeling, the EI electrostratigraphy information is used to interpret the potential gross stratigraphy of the traverses. In general, dry materials have higher resistivity than similar wet materials because moisture increases their ability to conduct electricity. This resistivity change, if indicated in the observed electrostratigraphy, can represent water table depths. Beneath the water table, silt, clay-free sands, and gravels will have a much higher resistivity than silts or clays under similar moisture condition because fine-grained materials are better conductors. In the bedrock, competent rock will have a high resistivity. Saturated fractured or weathered rock would show a much lower resistivity than the competent rock. Very high resistivities can indicate air filled voids.

The identified electric boundaries separating layers of different resistivities may or may not coincide with boundaries separating layers of different lithologic composition. These differences may result from the gradational presentation of the electrostratigraphy. Therefore, the electrostratigraphy can vary from the geologic stratigraphy, and caution should be exercised when reviewing and applying the electrical profiles.

2D EI Survey Case History

At a petroleum tank farm in Mechanicsburg, Pennsylvania, the Above Ground Storage tanks (ASTs) sit on solution-prone limestone bedrock. An investigation was performed to evaluate the location and distribution of potential collapse features near the ASTs and to define migration pathways of hydrocarbon in the soil and ground water for remedial design. As such, the location and trend of bedrock fractures were critical to placing monitoring wells where they would accurately characterize groundwater flow for designing a remedial approach.

Several geophysical surveys had been performed on the site with ground penetrating radar, gravity, terrain conductivity, and seismic refraction, but all had proven ineffective in producing subsurface models consistent with boring and well information. EI was performed to identify targets for a confirmatory boring and well program. The specific EI investigation included measurement and analysis of four parallel traverses within the tank farm, along roadways, and parking lots. The four profiles resulted in approximately 685 linear m of surveyed section to a depth of approximately 15 m.

The electrostratigraphy model from processing Traverse 2 is presented on Figure 4. Areas of high resistivity (greater than 300 ohm meters) were interpreted as competent limestone. Areas of moderate resistivity (200 to 300 ohmmeters) were interpreted as less competent (partially fractured and/or dissolved) limestone. Zones with lower resistivity (between 50-200 ohm meters) were interpreted as areas of soil, fractured limestone, and/or dissolved limestone. However, these areas may also be interpreted as soil where low resistivities occur near the ground surface. Finally, areas where resistivity was less than 50 ohmmeters were interpreted to represent potential soils, very fractured rock, or mud filled voids.

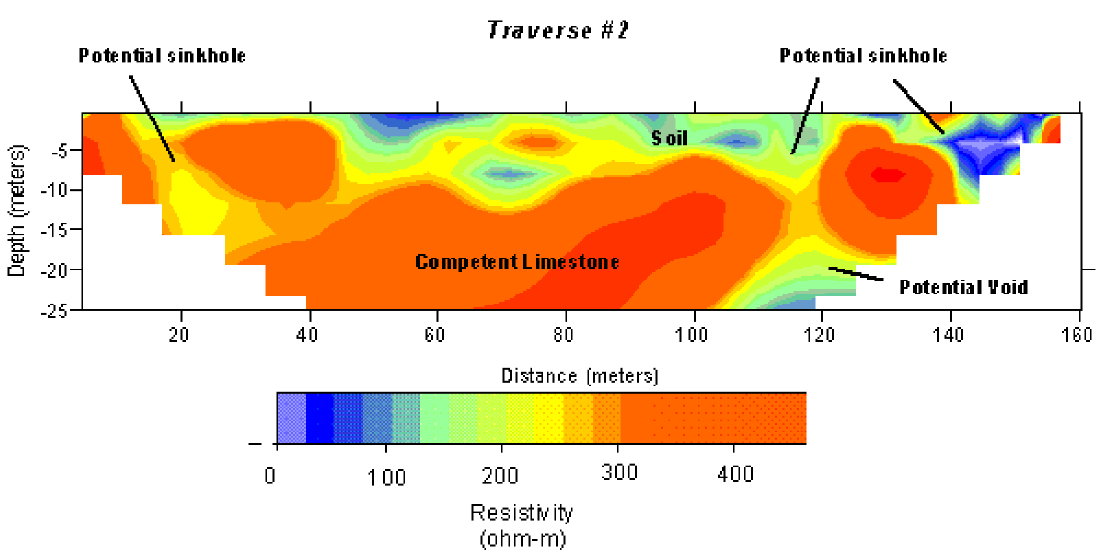

Figure 4 – 2-D Electrical Imaging model for Traverse 2.

Data evaluation at Traverse 2 suggested shallow bedrock from 0 to 40 meters (m) inline distance. Resistivity readings suggest that approximately 2 to 7 m of soil cover is present from 40 to 160 m inline distance. A zone of competent limestone was interpreted along the traverse from 40 to 100 meters at depth. Two zones of fractured limestone were suggested at inline distances of 20 meters and 120 meters. Within the feature at an inline distance of 120 m, a low resistivity zone was measured at 15 m below grade level (bgl). This zone could be interpreted as very fractured limestone and/or a mud-filled void in the bedrock. A shallow high resistivity zone underlain by a low resistivity zone was observed from an inline distance of 60 to 80 meters. This feature was interpreted as isolated blocks of competent limestone underlain by very weathered rock or soil.

Numerous direct push soundings were obtained to confirm bedrock depth and several rock borings/wells were installed to verify deeper features. There appeared to be a good correlation between the confirmatory intrusive program, air photographs, and the interpreted EI sections.

3D EI Survey Case History

A three dimensional survey was completed over Indian Echo Caverns in Hummelstown, PA (Figure 5) to identify the cavern morphology. The cavern is contained within the Ordivician Epler Formation, an interbedded limestone and dolomite. The cave maps indicate that the cavern entrance is along the Swatara Creek and the cave gets progressively wider with distance from the entrance (Figure 5). Near the Wilson Room, the cave narrows and speleothems are prevalent. Further from the entrance, greater than 100 feet, the cave widens again and breakdown and ceiling height increases. The 3-D grid overlies this described area and is shown on Figure 5.

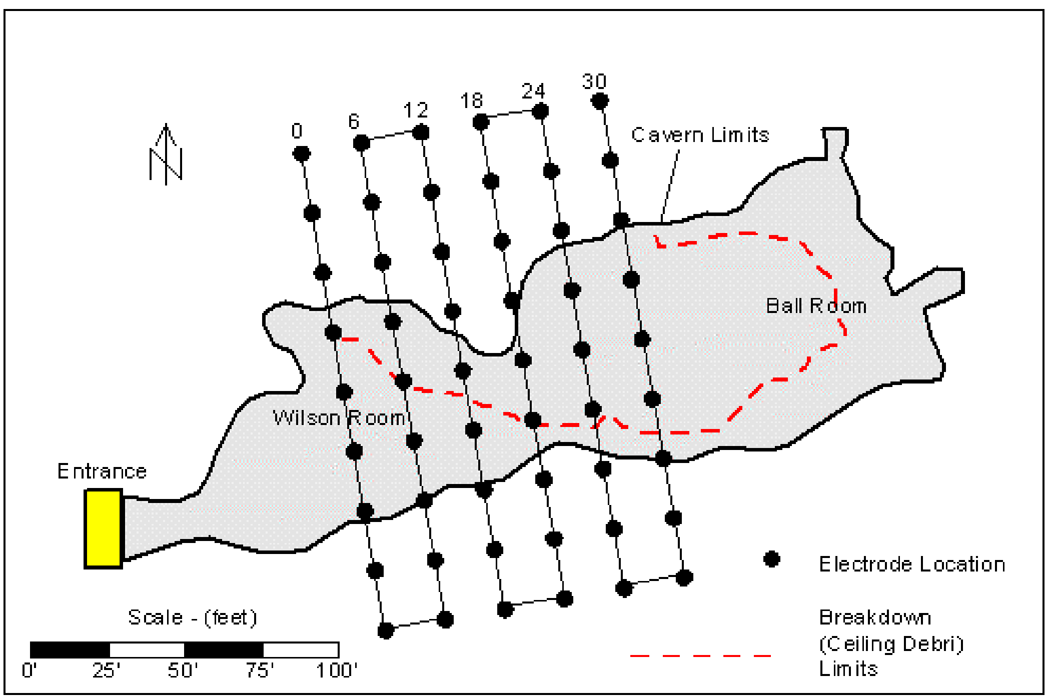

Figure 5- 3-D Electrical Imaging survey grid over Indian Echo Caverns.

The rectangular survey grid was configured so that maximum depth could be attained from a limited number of electrodes with a six meter electrode spacing. The grid was 48 meters by 30 meters, or 9 electrodes by six electrodes, and allowed for a maximum depth of 40 meters to be collected. The pole-pole method was used for this survey, which placed the B and N electrodes over 400 meters from the grid. Data was collected for approximately 6 hours.

Inversion modeling software, RES3DINV™ (Loke, 1997), was utilized to convert the apparent resistivities collected to modeled resistivity. The results are displayed in Figure 6 and are presented as vertical 2-D slices along the following locations of the model: y=0-6 meters, y=6-12 meters, etc.

The results presented in Figure 6 indicate a high resistivity zone directly beneath the survey grid. The high resistivity zone (greater than 18,000 ohm-meters), as shown on the profiles, changes size and shape and corresponds to distinct changes within the cavern. This zone appears smaller within the middle of the survey grid, profile y=12-18 meters and likely corresponds to the narrower cave passageway and the presence of numerous speleothems. The high resistivity zone widens and becomes larger in the last profile and corresponds to the widening of the cavern at the beginning of the ballroom. The smaller size of the high resistivity zone can also be related to the increase of breakdown material that occurs from the end of the Wilson Room to the Ballroom because of decreased void space.

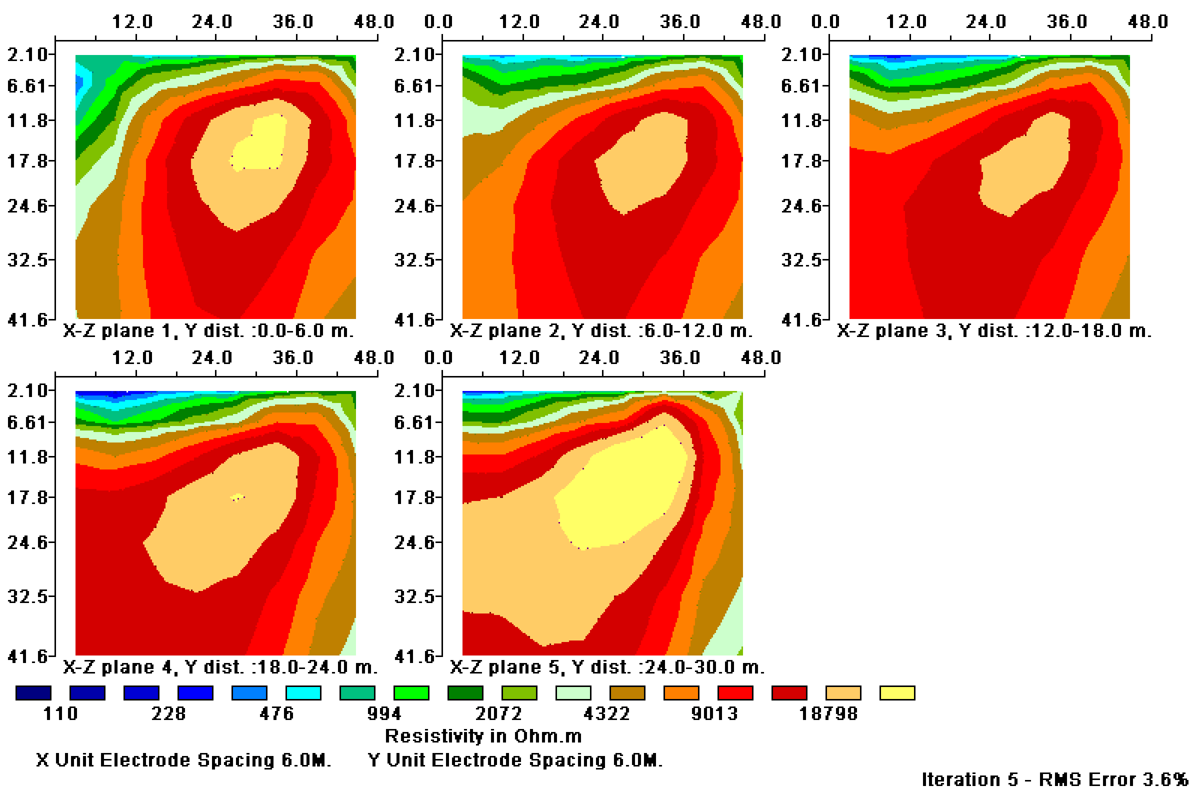

Figure 6- 3-D Electrical Imaging model showing vertical slices in the X-Z plane.

The resistivity profiles were examined closely to determine if changes in the overburden were present specifically in those areas that overly breakdown and rock debris. By using the EI system significant overburden changes, such as increased fracturing and water movement, should be noticeable on the resistivity profiles. This kind of information can provide some information into the potential weaknesses within the void ceiling and possibly future sinkhole development. Although the grid configuration provided a resolution that was not ideal for this type of analysis, significant changes within the overburden were not observed near the breakdown areas. These preliminary results suggest that the changes within the cavern ceiling are likely due to bedrock bedding changes and not increased fracturing.

Conclusions

Electrical Imaging techniques can be utilized to provide a cost effective characterization of the subsurface in karst environments. The EI method has been successful in identifying features of concern, in particular sinkholes, fractures, and voids. Both 2-D and 3-D surveys can be conducted along roadways, parking lots, developments, and airport runways to identify and monitor problematic areas that may cause structural damage. Furthermore, new developments in the EI system can allow for increased resolution with depth. These new developments, such as cross-hole surveys, can better characterize the subsurface and problem areas. New downhole cables have recently been developed to allow for downhole data collection. These techniques will allow for the use of EI for a much wider range of applications to obtain subsurface information.

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