# THREE DIMENSIONAL ELECTRICAL IMAGING

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**ABSTRACT**

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.

The 2-D surveys assume 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. The survey provides a more characteristic model of complex subsurface conditions. The paper presents three case histories. The first is over a known cavern in Hummelstown, PA. The second is along a road where a sinkhole had been repaired but now is collapsing again. The survey was performed to identify how big the area of concern may be. The third is a 3-D survey located adjacent to a large roadway collapse.

The limitation of the three dimensional survey over a two dimensional survey is that a three dimensional survey can take from 6 to 24 hours to collect depending on the number of electrodes. New advances in EI equipment will allow for significantly faster data collection.

## 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.

The development of computer-controlled multi-electrode resistivity survey systems and the development of resistivity 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 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.

## EI DATA COLLECTION

In application of a 2 D survey, 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. For EI data collection in this study a Sting/Swift multielectrode system manufactured by Advanced Geosciences, Inc. (AGI) of Austin, Texas was utilized. 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.

### 3-D 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 1). 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 survey (Li and Oldenburg 1992).

As with a 2-D survey, the operator programs the Sting for the chosen number of current pairs to energize and the maximum separation (in electrode spacing measurements) to measure the potentials. These two numbers determine the total number of measurements 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 most commonly used electrode configuration for 3-D surveys is the pole-pole array. Each electrode is used as a current electrode and the potentials at all the other electrodes are measured. Two electrodes (B and N) are placed at 10 times the overall grid size away from the grid in opposite directions. B and N represent electrodes at infinity. 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)

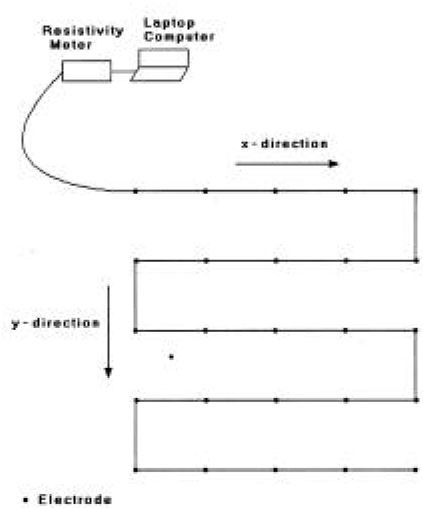


*Figure 1. A schematic diagram for one possible layout for a 3-D survey (Loke, 1997).*

## DATA MODELING AND INTERPRETATION

The apparent resistivity $p_a$, as measured by the EI system, is the average over 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 in this study is performed using RES3-DINV™ (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 3-D 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 modeling, the EI electrostratigraphy information is used to interpret the potential subsurface 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, clay-free silts and 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 inperpreting the electrical profiles.

**3-D EI Survey Case History #1**

A three dimensional survey was completed over Indian Echo Caverns in Hummelstown, PA (Figure 2) to identify the cavern morphology (Reccelli, Et al). 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 2). 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.

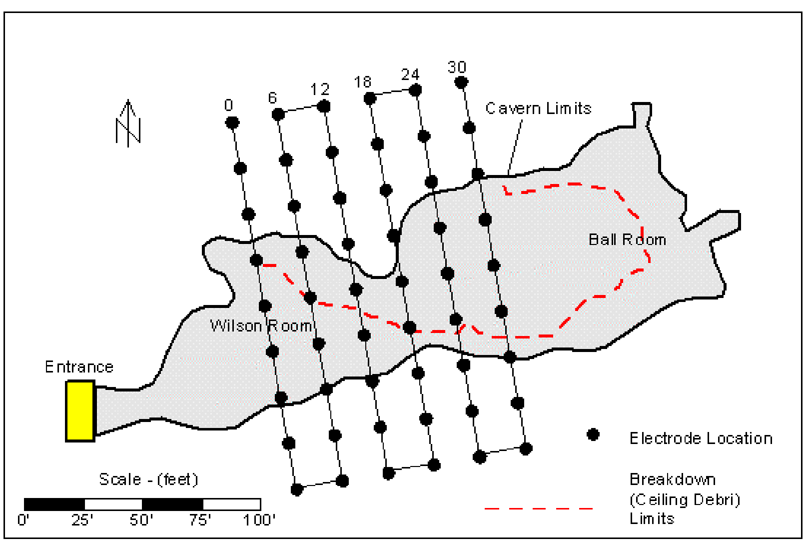


*Figure 2 - 3-D Electrical Imaging survey grid over Indian Echo Caverns (Courtesy of SAIC).*

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.

Modeling software, RES3-DINV™ (Loke, 1997), was utilized to convert the collected apparent resistivities collected to modeled resistivity. The results are displayed in Figure 3 and are presented as vertical 2-D slices along the following locations of the model: y=0-6 meters, y=6-12 meters, etc.

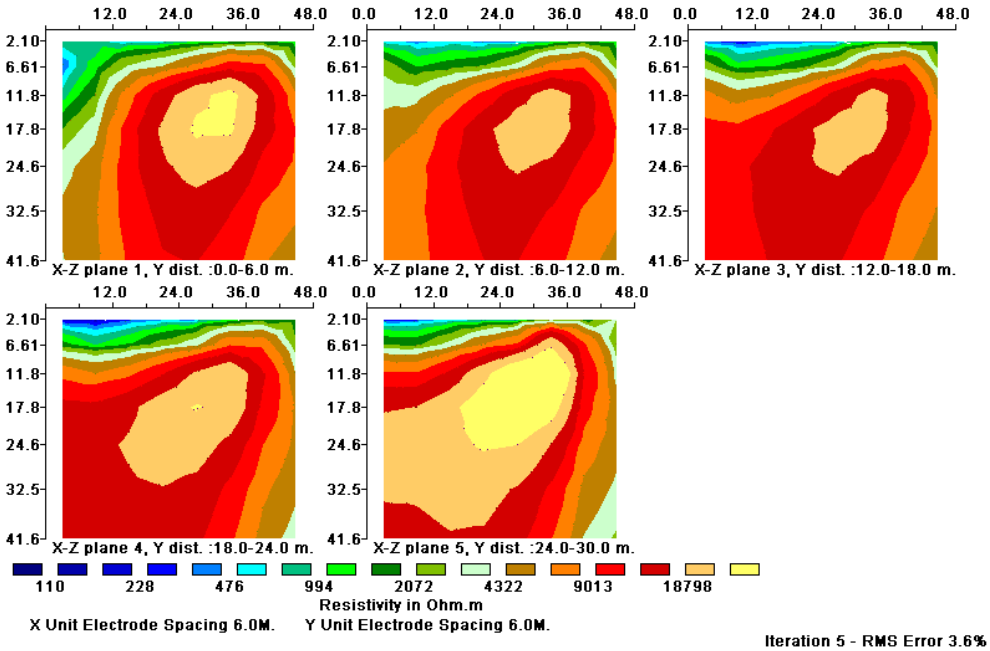


*Figure 3 - 3-D Electrical Imaging model showing vertical slices in the X-Z plane (Courtesy of SAIC).*

The results presented in Figure 3 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 area of the air filled cavern.

The resistivity profiles were examined closely to determine if changes in the overburden were present, specifically in those areas where breakdown and rock debris were present. 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 data can provide some information into the potential weaknesses within the cavern 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 (Reccelli, Et al).

**3-D EI Survey Case History #2**

A three dimensional survey was completed adjacent to a repaired sinkhole on Clifton Heights Road in Hummelstown, PA (Figure 4). The sinkhole had been repaired in July, 1999, but as of July 2000 the repair has collapsed approximately six inches. The survey was performed to evaluate if a throat may exist adjacent to the repaired sinkhole. The information could be used to repair the still active sinkhole.

*Figure 4 – Active sinkhole along Clifton Heights Road, Hummelstown, PA.*

The grid location is presented in Figure 5. The rectangular survey grid was configured so that maximum depth could be attained from a limited number of electrodes with a one meter electrode spacing. The grid was 6 meters by 7 meters, or 7 electrodes by 8 electrodes, and allowed for a maximum depth of 30 feet to be collected. The pole-pole method was used for this survey, which placed the B and N electrodes over 160 meters from the grid. Data was collected for approximately 5.5 hours.

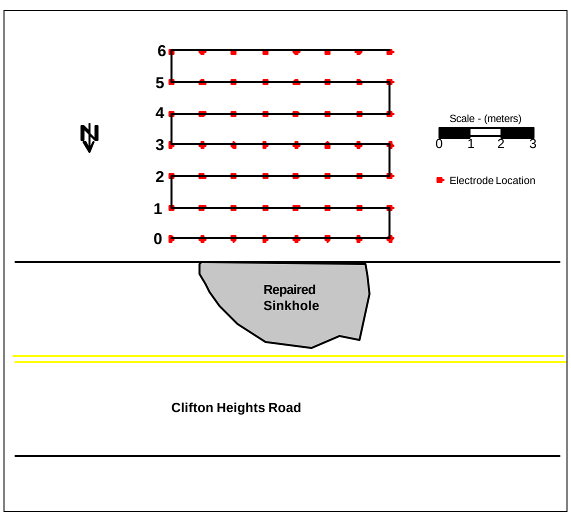


*Figure 5 - 3-D Electrical Imaging survey grid adjacent to the Clifton Heights sinkhole.*

As in Case History # 1, the modeling software, RES3-DINV™ (Loke, 1997), was utilized to convert the measured apparent resistivities collected to modeled resistivity. The results are displayed in Figure 6 and are presented as horizontal 2-D slices along the following locations of the model: y=0-1 meters, y=1-2 meters, etc.

The results are presented in figure 6. In The X-Z planes 0-1m and 1-2m a high resistivity zone is present from 0 to 4 meters in depth which suggests a void or very competent rock. The 2-3m, 3-4m, 4-5m, 5-6m, and 6-7m slices indicate a low resistivity zone from 1 to 3 meters in depths consistent with a clay filled zone. This may be the location of the throat where soil is still migrating away from the repaired sinkhole. The results provide specific targets to be characterized by exploratory drilling.

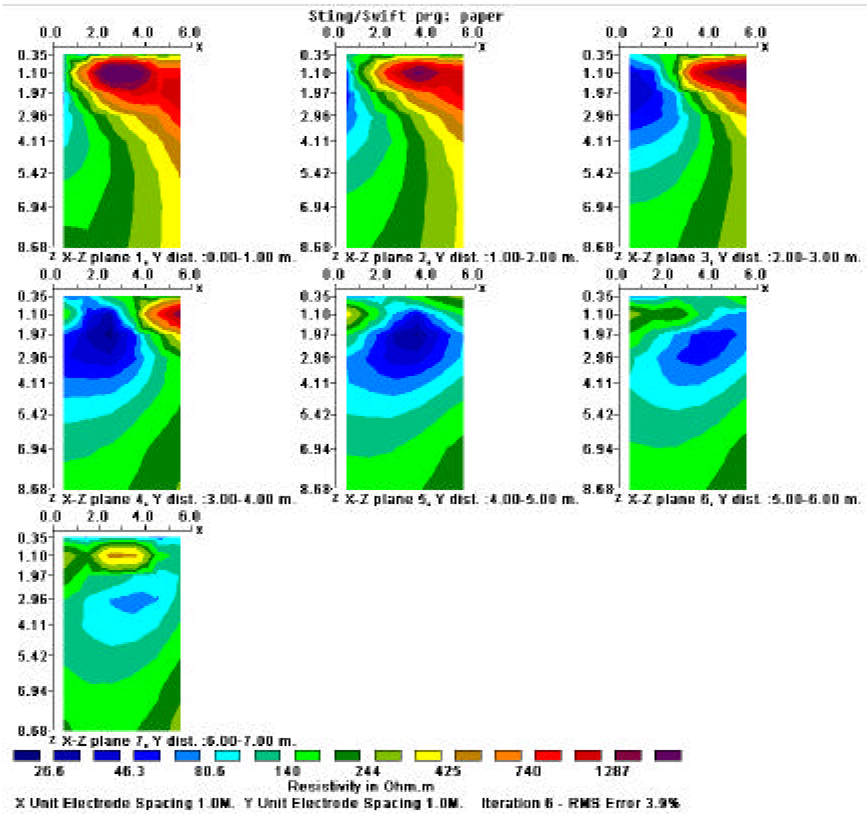


*Figure 6 – 3-D Electrical Imaging model showing vertical slices in the X-Z plane for Case #2.*

**3-D EI Survey Case History #3**

A significant collapse feature opened under Bull Frog Valley Road, near Hershey, Pennsylvania (Figure 7). The collapse feature was repaired and no further activity has been observed. A three dimensional survey was completed adjacent to the repaired collapse feature to identify additional features adjacent to Bull Frog Valley Road. The 3-D grid adjacent to Bull Frog Valley Road is shown on Figure 8.

The rectangular survey grid was configured so that maximum depth could be attained from a limited number of electrodes with a three meter electrode spacing. The grid was 18 meters by 21 meters, or 8 electrodes by 7 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 210 meters from the grid. Data was collected for approximately 6 hours. The grid location is shown in Figure 8.

Modeling software, RES3-DINV™ (Loke, 1997), was utilized to convert the measured apparent resistivities collected to modeled resistivity. The results are displayed in Figure 9 and are presented as vertical 2-D slices along the following locations of the model: y=3-6 meters, y=6-9 meters, etc.

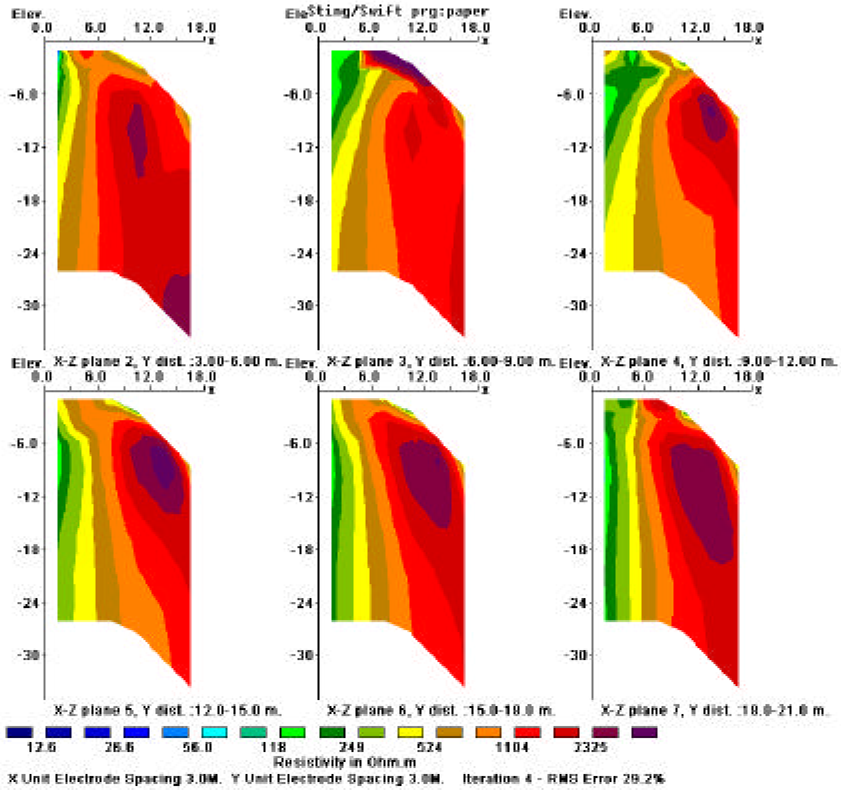


*Figure 7- 1975 sinkhole related collapse under Bullfrog Valley Road, near Hershey, PA.*

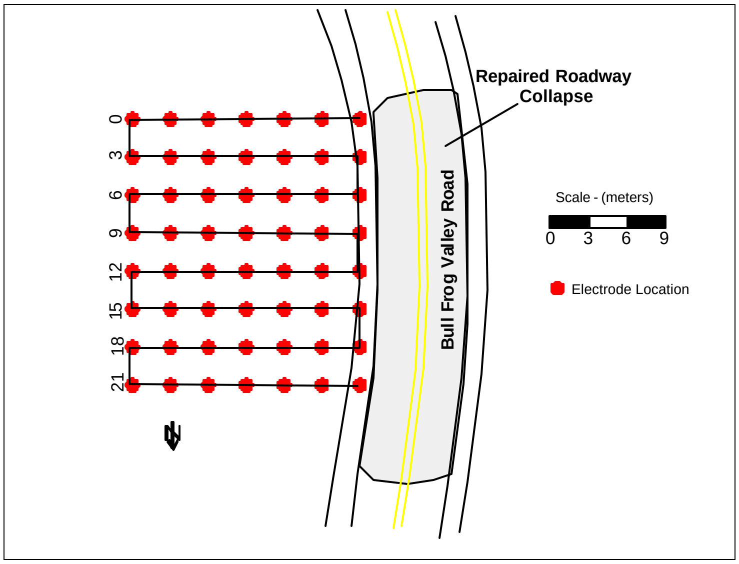


*Figure 8 - 3-D Electrical Imaging survey grid adjacent to the Bull Frog Valley Road sinkhole in Case History #3.*

*Figure 9 - 3-D Electrical Imaging model showing vertical slices in the X-Z plane along Bull Frog Valley Road. (Case History #3).*

The 3-D EI results indicate competent bedrock adjacent to the roadway. A low resistivity feature is located in X-Z plane 6-9m and 9-12m from 0 to 12m depths. This feature is consistent with a bedrock fracture or a throat of a potential sinkhole feature. Geoprobe in these areas verified the shallow rock near the road and thick soils along X-Z planes 6-9m and 9-12m.

**New Advances**

New advances in EI equipment will allow for significantly faster data collection. A new EI system, the SuperSting R8 IP manufactured by AGI (Figure 10), is a new multi-channel portable memory earth resistsivity meter with memory storage of readings and user defined measure cycles. This new instrument simultaneously measures up to 8 channels using a high power transmitter so that field data production can be significantly reduced (approximately 8 time quicker then the older Sting/Swift EI system). With a higher powered transmitter then the older Sting/Swift EI system, better data can be recorded in difficult locations where time-consuming stacking was the only alternative before.

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*Figure 10 – New SuperSting R8 IP EI Sytsem manufactured by AGI.*

## CONCLUSIONS

In this paper, 3-D EI surveys were successful at three separate sites. The 3-D EI survey has proven a valuable tool for mapping top of rock, potential voids, and sinkhole throats prior to collapse. In areas of very complex subsurface features the 3-D EI survey can provide a better representation of the subsurface features.

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