Subsurface Cavity Detection: Field Evaluation of Radar, Gravity, and Earth Resistivity Methods

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Gravity, ground-penetrating radar, and earth resistivity profiling as subsurface cavity detection methods were experimentally evaluated and compared in three geological environments. Verification tests showed that the gravity measurements located large cavernous areas but did not detect mud-filled troughs; the radar detected air-filled cavities at depths up to 4.6 m (15 ft) at one site, but only penetrated 3 m (10 ft) with inconclusive results at a second site, and could not resolve 0.6-m (2-ft) diameter vertical cylindrical cavities at another. Earth resistivity measurements using a pole-dipole electrode arrangement located cavities at all sites, indicating targets at depths up to 25 m (80 ft). Both air-filled cavities, including vertical cylinders, and mud-filled troughs were detected by using the resistivity technique, which gave accurate depth and size resolution. A large mud-filled trough was detected at a 9-m (30-ft) depth that extended below 30.5 m (100 ft). The earth resistivity technique was capable of delineating the irregularities of the bedrock at the soil-rock interface.

Sudden collapse or subsidence above unknown cavities results in extensive damage and property loss; corrective action costs are very high and are not always positive cures. Public costs for damages, property losses, and accidents would be greatly reduced if subsurface earth structural conditions along transportation routes and at building construction sites were known prior to final planning and construction.

At present, the only reliable method for locating underground cavities is by direct drilling. However, the time and cost of this method, because of the close spacings required between borings in order to reliably detect and delineate all possible underground cavities, generally restrict its use.

The subsurface cavities of most concern for highway stability and construction are those located within 15 m (50 ft) of the surface. They may be of various sizes and shapes and may contain various amounts of air, water, or soil. Conventional geophysical exploration techniques have been of limited success in detecting these cavities because of size resolution difficulties and the low contrast between the various observable cavity manifestations and the typical background conditions.

The presence of possible underground cavities may sometimes be noted from subtle indirect surface anomalies by using airborne sensing techniques. According to Warren and Wielchowsky (1), who used infrared photography, thermography, and side-looking airborne radar to study subsidence and collapse problems in several carbonate terrains, the results of aerial surveys can be a good starting point for further geologic and hydrologic studies. Newton (2) also has found remote sensing (multispectral photography and infrared imagery) useful in delineating features such as water loss in streams, geologic structures, and vegetative stress related to sinkhole formation.

Lakshmanan (3) and Colley (4) have both reported successful cavity detection using gravity measurements. Neumann (5) has also successfully demonstrated that detection of solution cavities is possible by gravity measurements if extreme care is taken to make the measurements on a very tight grid and to carefully account for topographic features.

Ground penetrating impulse radar is one of the most recent methods to show promise for subsurface cavity detection (6, 7, 8, 9). Results have shown detection capability, although only to depths of about 2.4 m (8 ft) in moist clay-rich soils; possibilities appear to be good if instrumentation is improved.

A third detection method worth evaluating is earth resistivity measurements. Bristow (10) has described a search method using a pole-dipole electrode array that can resolve small underground cavities. He used a graphical data display technique that allowed a bearing to be obtained on the location of the cavity, as well as a prediction of its size and shape. Bates (11) has reported successfully detecting cavities using Bristow's method and modified the search procedure to allow more redundant data to be collected. Shallow voids have been detected by using a mobile equatorial dipole electrode array (12). The Federal Highway Administration has also evaluated subsurface cavity detection methods (13).

The three search methods selected for evaluation

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(gravity surveys, ground penetrating radar mapping, and earth resistivity surveys) were tested at sites in Alabama and Florida. All sites were in areas where sinkhole formation is known to be active. At each site all surveys were made over a common base grid pattern composed of a rectilinear array of traverse lines equally spaced at a distance of 3 m (10 ft).

INSTRUMENTS USED AND SURVEY METHODS

Gravity Survey

A Lacoste model G gravity meter was used in the evaluation tests. It had a vernier scale permitting gravity readings to 10^{-8} m/s^2 (0.001 milligal). Repeatability is within 10^{-7} m/s^2 (0.01 milligal).

At the test sites the elevation of each grid point was measured to the nearest 30 mm (0.1 ft) so that elevation variations could be compensated for in the gravity readings. In the gravity survey a minimum of two measurements were made at each station, and the measured values then averaged. Gravity data analysis and display were in the form of a Bouguer gravity map compiled for each test site. Gravity values to 10^{-8} m/s^2 (0.001 milligal) and contour intervals of 2×10^{-7} m/s^2 (0.02 milligals) were plotted on these maps.

Radar Survey

A van-mounted radar system manufactured by Geophysical Survey Systems, Inc., that transmits a base-band voltage pulse of approximately 3 ns was used for the radar survey. The system radiates the quasi-gaussian pulse waveform into the earth by means of a broad-band antenna. The radiated signal is an electromagnetic transient having a frequency spectrum with -3 dB points at about 30 MHz and 120 MHz. The pulse peak power is 35 W with an average power of 5.2 mW. A two-way transmission loss of 110 dB, indicating the ratio of peak radiated power to the minimum detectable received signal power, is claimed for the system.

The radar field data were collected in a continuous profile by pulling the sled-mounted antenna assembly across the area of interest. Real-time profile data were displayed on an oscilloscope and on a graphic recorder, while simultaneously being recorded on a magnetic tape recorder for subsequent laboratory playback and analysis.

The data consist of signals reflected or scattered from subsurface anomalies such as voids. Depth to the target is indicated by the time delay between the pulse transmit time and the signal receive time.

Resistivity Survey

Instrument and Method

The earth resistivity surveys were made using a Keck model IC-69 earth resistivity instrument. The instrument is a dc system obtaining power for earth current from dry cell batteries having a total power of 630 V. Resistance could be measured over the range 0.001 to 1000 Ω, and the dial read to 1 part per thousand.

Porous-pot electrodes were used as the potential electrodes to eliminate problems and errors caused by galvanic action between metal electrodes and the soil. Since the contact resistance between the bottom of a porous-pot electrode and the ground can be as high as several thousand ohms, copper-clad steel electrodes were used as the current electrodes.

The main differences among the various electrical resistivity geophysical profiling methods are in the electrode array patterns used and in the manner in which the electrodes are moved or scanned over the area being surveyed. The methods of resistivity data analysis and interpretation also differ with the different electrode arrays. The pole-dipole array has had less use and shown the greatest potential for detecting underground cavities and predicting their depths and locations.

Pole-Dipole Earth Resistivity Electrode Array

Theory and Method

The pole-dipole electrical resistivity survey method is based on a four-electrode, straight-line array configuration in which the current sink electrode is located at infinity, and the potential electrodes are separated from one another by a fixed minimum distance proportional to the desired resolving power of the system. The potential electrode pair is located at various positions along the array line on both sides of the current source electrode as the means of vertically sounding the subsurface below the current source electrode. The current source electrode is moved ahead at suitable incremental distances to provide horizontal profile scanning. This array is illustrated in Figure 1.

In order that the equipotential surfaces be hemispherical and concentric about the source electrode, the sink electrode must be located at an effective infinity, which is generally 5 to 10 times the largest value of detection penetration depth of interest. The overlapping survey procedure can be described as follows for a typical 30-m (100-ft) penetration depth survey:

1. Place the current source electrode, C_1, as shown in Figure 1 at the first traverse station;
2. Place the current sink electrode, C_2, at a minimum distance of 150 m (500 ft) (5 r_2) and behind C_1 on a preestablished traverse line [having already decided that the maximum potential electrode scan distance from C_1 will be 30 m (100 ft)];
3. Place the potential electrodes, P_1 and P_2, at preestablished station markers 3 and 6 m (10 and 20 ft) respectively on the sink electrode side of C_1, and obtain the resistance reading;
4. Repeat step 3 above with the potential electrodes, P_1 and P_2, at preestablished station markers 6 and 9 m (20 and 30 ft) respectively on the sink electrode side of C_1, obtain this resistance reading, and continue the movement of the P_1 and P_2 electrodes in this manner until a final potential reading is obtained at 27 and 30 m (90 and 100 ft) from C_1;
5. Next, place the potential electrodes at preestablished 3-m (10-ft) interval station markers on the opposite side of C_1 from C_2, and obtain resistance readings at each station pair out to the 30-m (100-ft) limit, which completes the survey procedure for the first current station position for C_1;
6. Move C_1 up the traverse line a distance of 12 m (40 ft), and obtain resistance readings over the 30-m (100-ft) scan zones on each side of this current station; and
7. Repeat step 6 above until the complete traverse line is surveyed. This procedure gives four overlapping resistance readings for each 3-m (10-ft) spaced potential electrode pair station to a depth of more than 15 m (50 ft) as the survey proceeds.

Figure 1. Pole-dipole earth resistivity electrode array.

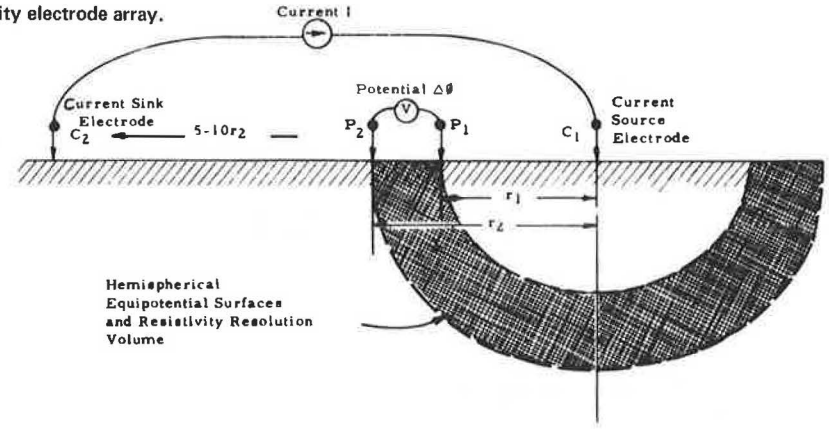
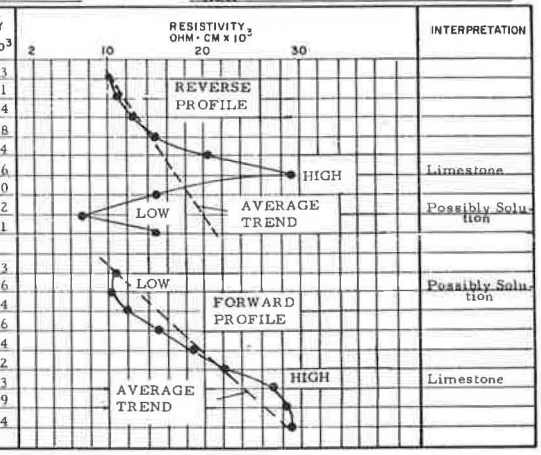


Figure 2. Sample resistivity traverse data sheet with anomalies marked.

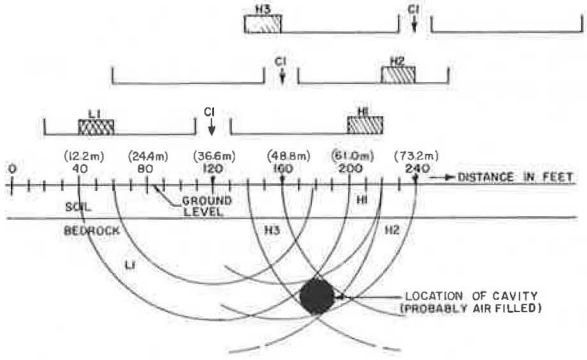
PROJECT SwRI 14-4013 SITE 1-59 ALA
TEST NO #7 AREA 1-59, Birmingham, Alabama Grid Col. A
DATE 28 Oct. 74 Monday 12:50 to 1:05 pm CURRENT PROBE POSITIONS +280 (Std. 387+301 +1000
WEATHER CONDITIONS Fair Warm OBSERVER H&K

P-P (m)	P-P (m)	READING OHMS	FACTOR 10^3	RESISTIVITY OHM-CM x 10^3	INTERPRETATION
-3 to -6	4.5	2.67	3.83	10.23	
-6 to -9	7.5	0.969	11.49	11.11	
-9 to -12	10.5	0.550	22.98	12.64	
-12 to -15	13.5	0.386	38.30	14.78	
-15 to -18	16.5	0.394	57.45	22.64	
-18 to -21	19.5	0.365	80.43	29.36	Limestone
-21 to -24	22.5	0.138	107.25	14.80	
-24 to -27	25.5	0.048	137.89	6.62	Possibly Solution
-27 to -30	28.5	0.090	172.36	15.51	
3 to 6	4.5	3.01	3.83	11.53	
6 to 9	7.5	0.902	11.49	10.36	
9 to 12	10.5	0.511	22.98	11.74	Possibly Solution
12 to 15	13.5	0.388	38.30	14.86	
15 to 18	16.5	0.321	57.45	18.44	
18 to 21	19.5	0.275	80.43	22.12	
21 to 24	22.5	0.252	107.25	27.03	Limestone
24 to 27	25.5	0.203	137.89	27.99	
27 to 30	28.5	0.165	172.36	28.44	



Note: 1 OHM-CM x 10^3 = 10Ω-m.

Figure 3. Graphical method of locating a resistivity anomaly.



Graphical Data Analysis

The success of the graphical analysis used is largely achieved through the spatial redundancy of the field data; as a result target ambiguities and false interpretations are minimized, and improved cavity size and shape indications are derived.

It is best illustrated by examining a sample of the field data. The basic field measurements were recorded on specially prepared data forms. Figure 2 is a sample data sheet showing the recorded instrument readings and calculated resistivity values, and a graph of a derived resistivity profile. The first column on the data sheet is the potential-pair electrode distance from the current source electrode; the second column lists the distances from current electrode to the midpoint between the potential electrodes; the third column is the resistivity instrument reading in ohms; the fourth column is the geometrical factor required to calculate the apparent resistivity for the distances listed in the first column, using the resistances recorded in the third column; and the fifth column is the calculated value of the apparent resistivity.

The pole-dipole geometrical factor in column four is calculated from the relationship

$$KPD = 2\pi r_1 r_2/(r_2 - r_1) \qquad (1)$$

where r_1 and r_2 are the distances of the potential electrodes, P_1 and P_2, from the current source electrode, C_1, as illustrated in Figure 1. The basic principles on which the geometrical factor, KPD, is derived are discussed in many texts on geophysical prospecting (14).

Graphs of the forward and reverse apparent resistivity profiles are plotted on the data sheet as shown in Figure 2. Those points on the profiles that indicate resistivity perturbations above or below the average profile trends are next identified and marked for transfer to a scaled drawing used to graphically locate the anomalous underground resistivity structures.

An example of the scaled drawings used in the graphical analysis is shown in Figure 3 (this is not related to

the data of Figure 2). The distance along the ground surface representing the survey traverse is marked, and the consecutive positions of the current probe are shown by the arrows marked C_1. The perturbations interpreted from the forward and reverse resistivity profiles for each current electrode station, C_1, are denoted on the bracketed lines drawn above the ground surface line. The high resistivity anomalies in this example are labeled H1, H2, and H3. With a compass centered at each C_1 location on the ground surface line, arcs are drawn at distances representing the bounds of the high resistivity anomaly with respect to the current probe position to give the pairs of circular arcs labeled H1, H2, and H3, corresponding to the observed anomalies. The space where the three sets of arcs intersect is the graphically derived location of the underground structure responsible for the high resistivity perturbations. The single isolated low resistivity perturbation shown in the example of Figure 3 is insufficient to provide a graphical intersection with other low resistivity perturbations and is therefore ignored. A useful arbitrary guide for taking advantage of the redundancy of the overlapping field measurements is to require the intersection of a minimum of three arcs at a common location before that location is interpreted with any confidence as a probable underground anomaly. Moreover, as illustrated in Figure 3, the arcs are drawn only in the 90-deg sectors corresponding to either the forward or reverse profiles containing the perturbations being used. The reason for this is that the distortions of the equipotential lines (represented in a first order manner by the circular arcs) are very weak if the perturbing anomaly is located in the opposite 90-deg sector.

The pairs of arcs drawn for each resistivity perturbation describe not only the resistivity perturbations in the vertical plane along the ground traverse line but also apply, to some extent, to a three-dimensional spherical shell segment extending laterally on each side of the traverse line. It has been speculated by both Bristow (10) and Bates (11) that this apparent lateral field of view away from the traverse line is contained within an angle of about ±25 deg on each side of the traverse line relative to the source electrode location.

FIELD TEST RESULTS

Medford Cave Test Site, Reddick, Florida

The first test site selected is near Reddick, Florida, south of Gainesville. It has accessible air-filled underground limestone solution caverns known as Medford Cave. The underground caverns have rooms ranging in size to 12 m (40 ft) in width, and many smaller passages. These caverns are primarily in miocene Hawthorne formation limestone of the Alum Bluff group, but deeper portions are in eocene Ocala limestone. The subsurface cavities average about 3 to 9 m (10 to 30 ft) below the surface in most places, although some rooms reach depths down to 24 m (80 ft). The 0.9 to 1.8 m (3 to 6 ft) of soil on top of the limestone is sandy clay containing some phosphate and weathered limestone.

The first tests were made at this site because of its known features.

Gravity Survey

Major caverns were detected by their gravity anomalies, and a few other suspicious areas were noted. The survey consisted of gravimeter measurements at 563 stations on a 3-m (10-ft) rectilinear grid. The large near-surface joints and cracks that ran in many directions from the main rooms of the cavern caused a very high level of lithological noise that made recognition and interpretation of the gravity anomalies more difficult.

Two gravity depressions were noted near relatively large cavities. In these locations the cave was under about 6 m (20 ft) of overburden. In the vicinity of the largest of these anomalies, the roof thickness was 3 to 5 m (10 to 15 ft).

Figure 4 is an outline map of the cave with the cavity detection results of the three remote sensing methods superimposed. The principal gravity anomalies are the shaded areas designated by the symbols A through E. Anomaly A was not verified. Anomaly B was drilled, but no cavity was found. Anomaly C probably results from a composite effect of the large and small caves, with an added effect from the large sinkhole near the small cave. Anomalies D and E are over the main cave complex. A number of smaller gravity anomalies were noted but not verified. The unexplained anomalies were probably caused by cracks and fractures in the area.

Thus the gravity method detected only the largest room of the Medford Cave complex with any certainty. Negative drill verification results of gravity anomalies having magnitudes comparable to those associated with the large room tend to reinforce this uncertainty of detection.

Radar Survey

The final results of the radar survey are shown in Figure 4. There are six anomalous subsurface areas. One is located over the main room of the cave and another over one edge of it. The largest of these was verified to be the cave ceiling at a depth ranging from 3 to 4.5 m (10 to 15 ft). Another anomaly, that in the vicinity of row 16, column 24, in the lower left of Figure 4, is located near a fairly large room of the small cave section. The validity of this radar detection was not tested by drilling, but there is a fracture in the roof of this room that extends in the direction of the indicated radar anomaly. The small anomaly near row 13, column 20, is over a large fractured area, a part of which was a man-sized passage. The surveyed depth below surface in this area was about 5.5 m (18 ft). The large irregular anomaly centered on about row 12, column 15, was not drilled, but its depth below the surface as predicted by radar ranged from 2.7 to 5.2 m (9 to 17 ft). The other sensing methods showed no significant anomalies corresponding to this location. The curved radar anomaly centered at about row 16, column 12, was drilled at grid row 15.5, column 11. Rock was encountered at about 0.9 m (3 ft) and continued to a depth of 16 m (52 ft) where drilling stopped. The radar return was probably from the soil-limestone interface.

Thus the radar technique was fairly successful at the Medford Cave test site. It detected known or verified limestone cavities that were not more than about 4.6 m (15 ft) below the surface. It also detected soil-rock interfaces.

Earth Resistivity Survey

Eleven lines were traversed at the Medford Cave test site using the pole-dipole electrode array with very good results. Over 55 high resistivity anomalies were mapped and interpreted to show the depth below the surface of their tops and bottoms. A large number of these were located in the known cavernous area. There were also indications of deeper subsurface cavities in at least one location under the floor of another void. One of these was verified by the cave mapping crew, who found a deep narrow room approximately 3 m (10 ft) high located at a depth of about 17 m (55 ft) below the main room whose floor

Figure 4. Outline of Medford Cave with location of underground anomalies.

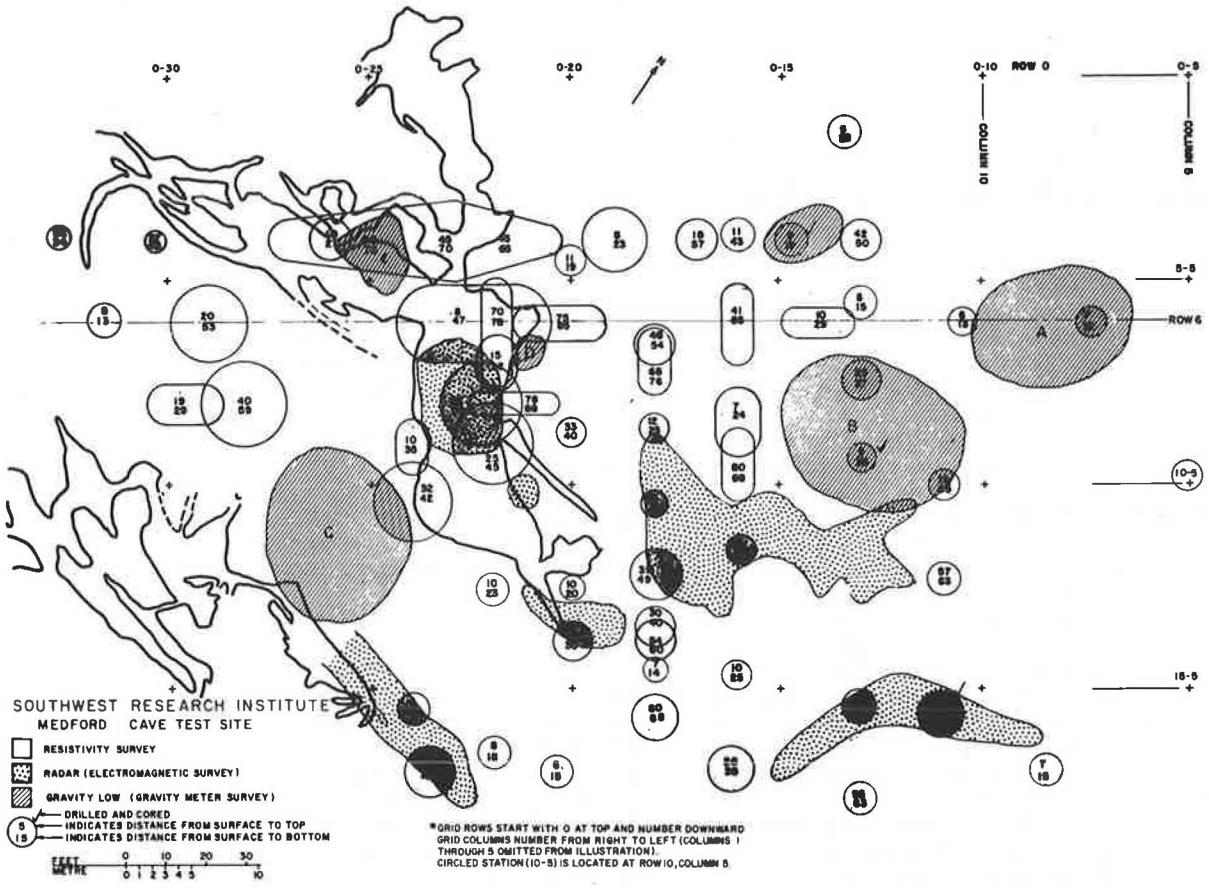
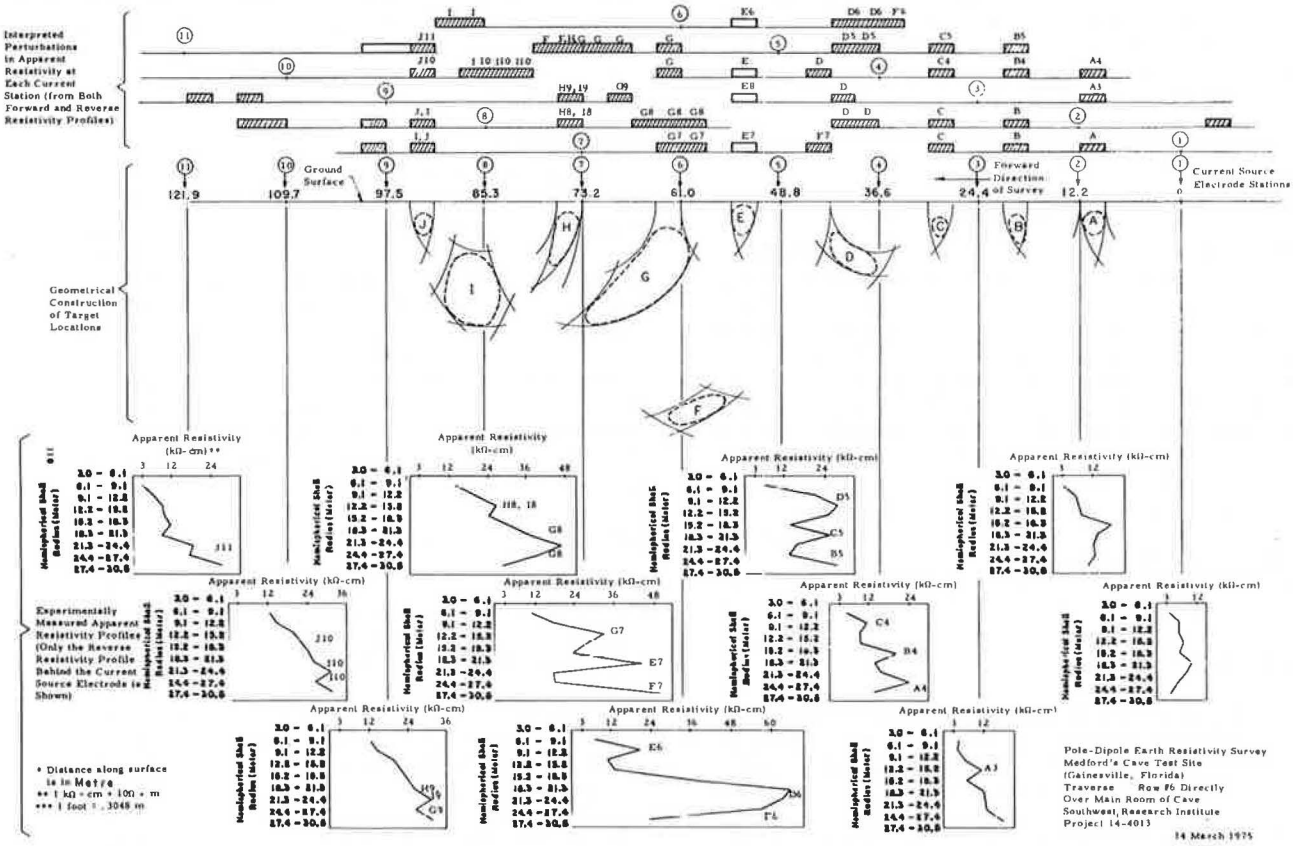


Figure 5. Pole-dipole resistivity survey results.



was at about 8 m (25 ft) below the surface).

The results of this survey are also indicated on the map in Figure 4. The high resistivity indications are plotted as if they were spheres or cylinders. The dimensions shown for these anomalies are the predicted top-to-bottom dimensions of the anomaly as derived from the graphical analysis. In order to determine more detailed horizontal extensions of these anomalies, it would be necessary to obtain resistivity readings on a much tighter survey grid.

Figure 5 is an example of pole-dipole resistivity results found for the Medford Cave test site. The data in this figure are from a traverse along row 6 crossing over the main room of the cave. The circled numbers along the ground surface line indicate the current source electrode positions analogous to those illustrated previously in Figure 1. The high resistivity perturbations that were interpreted for each current station are indicated by the shaded blocks in the upper section of the figure. The lower portion of the figure shows some of the measured apparent resistivity profiles from which the perturbations were derived. Only the reverse profiles are shown because of limited space.

Examples of high resistivity interpretations are identified on the lower section of the figure and labeled A3, A4, B4, etc. These high perturbations are transferred as arc radii to construct the subsurface zones of intersection as discussed earlier. The cavity labeled G in Figure 5 is the large cylindrical pattern on row 6 that extends from about column 20 to column 24 in Figure 4. The roof and floor of this cavity are interpreted to be at 2.4 and 14 m (8 and 47 ft) respectively.

Three test borings at the Medford Cave site did not encounter any additional cavities. Since an extensive verification description of most of the surveyed area could be obtained by mapping the cave, the various detection results indicated by the resistivity tests as well as by the other survey methods were verified by comparison with the cave map.

In summary, the resistivity survey was successful in detecting all of the known voids associated with the survey paths traversing the Medford Cave test site. Many more anomalies were detected away from the mapped cave area and are predicted to be inaccessible and unmapped voids in the limestone bedrock.

US-19, Chiefland, Florida

A second field test site selected in Florida was located about 3 km (2 miles) north of Chiefland, Florida, along US-19. This area is underlain by the Ocala limestone of the Jackson age in the eocene series. It is generally covered with sand from the ground surface to a depth of about 3 m (10 ft), then a fairly heavy clay-sand mixture (argillaceous sand) down to about 4.6 to 6 m (15 to 20 ft). Soft limestone is generally found below the surface soil materials, and harder limestone exists at greater depths.

Sinkhole cavities in this area are generally in the form of vertical pipes a meter or two (a few feet) in diameter, with depths of 15 m (50 ft) or greater. Some pipes are air filled, and some are filled with sand and clay mixtures.

The ground penetrating radar and earth resistivity systems were evaluated at this site.

Radar Survey

The results of the radar survey at US-19 showed good penetration depth but no verified cavity detection.

The electromagnetic attenuation constant of the earth materials for the radar signal frequency range was low enough in this area to permit two-way radar signal penetration to maximum depths of about 9 m (30 ft). The propagation velocity of the radar signals was high in the relatively dry sand, causing signal wavelengths to be too long to resolve the small diameter cavities of the area. A shorter wavelength radar system with an improved two-way transmission loss capability should find most of the piping in this Florida location.

Earth Resistivity Survey

Particularly good results were obtained from the resistivity survey. Only the high resistivity anomalies interpreted are shown on the map in Figure 6, although some low resistivity anomalies were found in the moist sandy clay at some depths. Seventy-eight high resistivity target areas were marked. Because of the limited time and availability of drilling equipment, only 13 verification holes were drilled. From these, five different air cavities were encountered. In those test borings where the predicted cavities were not found, it is possible that, because of the small diameters of the vertical-pipe voids, their localized position was missed by the drill.

The effectiveness of the pole-dipole resistivity survey technique is shown clearly by the verification tests at grid location C, 55.5. The resistivity anomaly interpreted at this location was a high perturbation having a graphically indicated depth range 2.7 to 6 m (9 to 21 ft). The drill tests showed a cavity extending from 4.3 to 8 m (14 to 25 ft). The absence of this cavity at positions of ±1.5 m (5 ft) on each side of the grid position indicated the limited lateral extent of the detected cavity. Similarly, another anomaly was interpreted as being due to a small cavity near the surface at grid location E, 28. Drill verification of this anomaly showed a 0.6-m (2-ft) diameter, 2.7-m (9-ft) deep pipe concealed under only 0.3 m (1 ft) of surface soil.

Interstate 59, Birmingham, Alabama

The third site selected is in Birmingham, Alabama. It is a portion of the highway right-of-way along Interstate 59 in the Roberts Industrial Park area located 73 m (240 ft) from a very large limestone quarry. The test area is mostly clay underlain by a light gray Ketona dolomite having an irregular surface at depths in the range 9 m (30 ft). Much of the layered limestone is badly cracked and fragmented, probably by shocks from explosive charges used in the quarry. The entire area is very active with sinkhole formations of various sizes and depths.

All three detection methods were evaluated at the I-59 test site, but only the earth resistivity method was successful in locating potential subsidence areas. The radar tests had extremely high electromagnetic attenuations in the soil, which resulted in limited depth penetration. The gravity survey was aborted because ground vibrations caused by the heavy traffic flow at close proximity to the measurement stations disturbed the instrument. (The traffic flow on I-59 at this location averages about 75 000 vehicles/d, a great many of which are large trucks.)

Earth resistivity measurements were successful at the site in spite of two problems encountered: (a) A chain link fence with ground-contacting metal parts ran parallel to the highway at distances of 3 to 21 m (10 to 70 ft) from the desired resistivity traverse lines; and (b) very strong dc earth currents, apparently caused by the various manufacturing processes in the area, such as a metal plating plant, caused occasional problems in making accurate resistivity measurements. At various times during the day these slowly varying earth currents were so strong that the survey was interrupted until after the disturbances stopped.

Although no subsurface voids were found, a total of

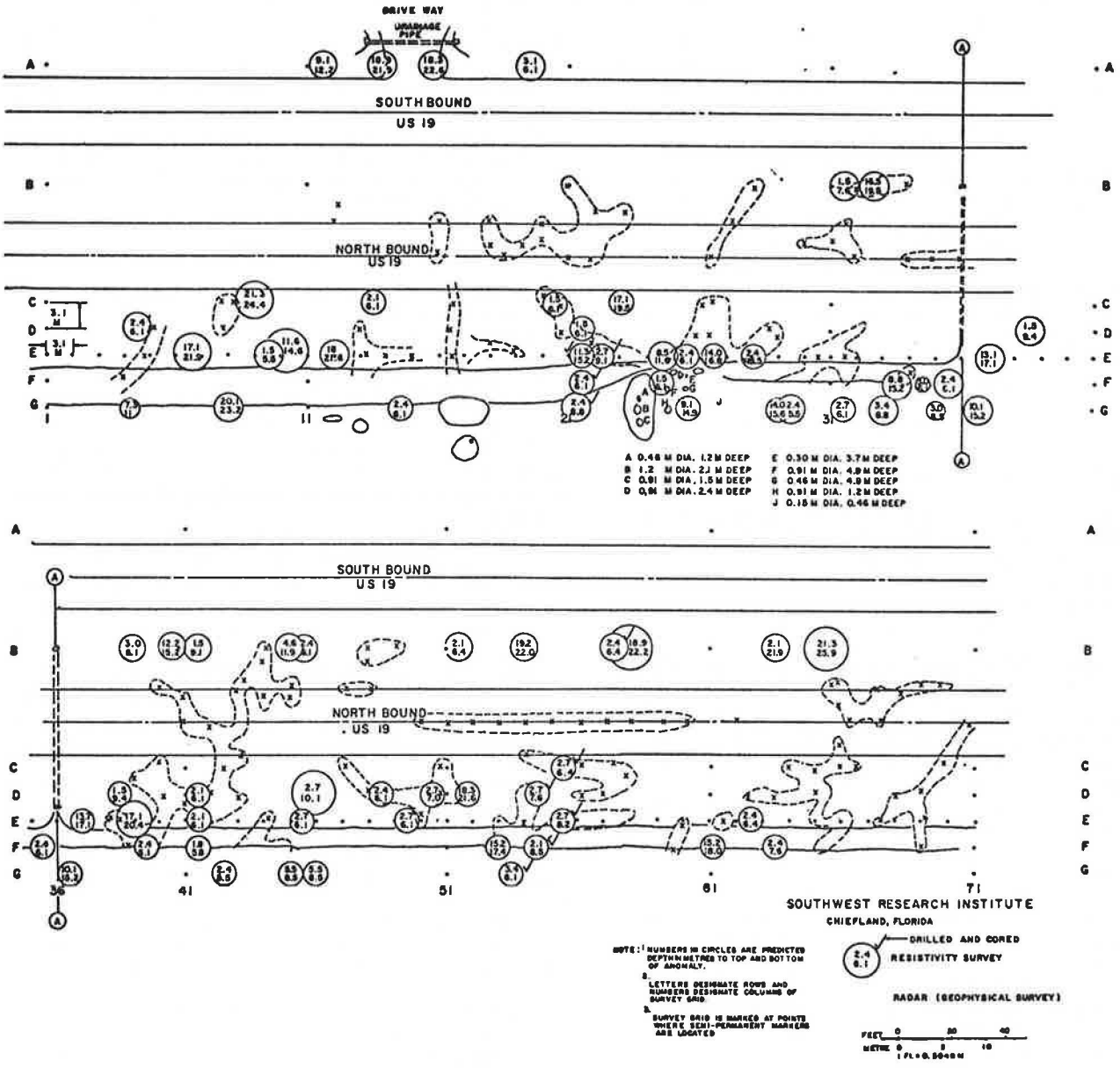
92 high resistivity anomalies were detected. Of this number, 33 were augered to rock and 2 were cored into the rock. All of the high anomalies except 2 were caused by the soil-bedrock interfaces, some of which were thin rock strata over mud-filled slots. The two high anomalies not caused by bedrock were interpreted as the base structures of highway light poles near the traverse path. In all of the verified subsurface anomalies, the predicted depth was correct to within 0.6 to 0.9 m (2 to 3 ft). A number of low resistivity areas were also detected, usually under a rock layer, indicating a mud- or solution-filled slot or trough.

Three areas having low resistivity anomalies beneath higher resistivity soil or rock were verified as having large mud-filled subsurface troughs. At one location a shattered rock layer about 0.6 m (2 ft) thick was encountered. The verification auger broke through the rock at about 10 m (34 ft) and hit very soft mud that extended to a depth greater than 31 m (100 ft) below the surface. A second mud-filled trough was verified in an area where clay soil was found to a depth of about 7.6 m (25 ft) and, below this very soft mud, to a depth greater than 19 m (63 ft). A third and a fourth mud-filled trough were found in the vicinity of an earlier construction fill in the 6 to 9-m (20 to 30-ft) and 9 to 15-m (30 to 50-ft) depth ranges respectively.

From the larger scale interpretations of the resistivity anomalies, there appears to be a deep mud-filled channel crossing under the highway in this area. Sinkhole activity was found on the north side of the highway where there is one sinkhole near the fence. Available drilling logs also showed soft mud to depths greater than 32.9 m (108 ft) in the median. On the south side of the highway there are a number of sinkholes at the surface along the right-of-way. These sinkholes have funnel type vents in the bottom where water enters underground, probably to feed larger underground channels extending under the highway.

With the additional knowledge of the average soil depth to bedrock, available from drilling logs of the area, the close-spaced resistivity data can be more readily interpreted and understood. Figure 7 shows the vertical

Figure 6. Underground anomalies as indicated by radar and earth resistivity survey techniques.



resistivity profile along one of the survey lines parallel to the highway about 3 m (10 ft) from the pavement. The results of seven of the test borings are also shown in this figure. The bars above the profile show the current electrode positions and the extent of the traverse on each side of the current electrode. The coded blocks on these lines show positions of high and low resistivity anomalies that enable geometrical constructions of the subsurface profile.

The three small air-filled cavities were very strong highs on the data graphs, but were not verified by drilling. The isolated low resistivity anomaly below the 119-m (390-ft) marker was not verified, but was a strongly indicated anomaly. The undulating bedrock surface caused resistivity highs whenever a near-surface peak, or pinnacle, was encountered during a traverse, and numerous test borings verified their presence.

In summary, the earth resistivity survey was successful at the I-59 site, revealing not only the soil-bedrock interfaces, but also the mud-filled slots, pinnacles, and overhangs that were verified by drilling. Enough information was gained from the data to allow a conceptual drawing of the complete subsurface profile structure to a depth of greater than 15 m (50 ft) along a survey line 305 m (1000 ft) long.

CONCLUSIONS

Three methods for surface detection of remote underground cavities were field tested and evaluated. These methods were: (a) gravity surveys, (b) electromagnetic subsurface profiling (ground penetrating radar), and (c) earth resistivity surveys.

The following conclusions are drawn from the results.

1. Earth resistivity surveys were the most successful of the three methods evaluated. The method was successful at three field sites having different geologic structures. Both the size and depth interpretations of the detected cavities were generally good (as verified by subsequent verification drilling). Voids were detected at depths up to 25 m (80 ft).

2. The information from close-spaced pole-dipole electrode resistivity surveys can be used with basic geological information to prepare vertical profiles of subsurface structures.

3. The currently available radar instruments can locate subsurface voids in some materials, but cannot reliably do so in all materials because of the variations in earth material electromagnetic properties. The penetration depth by the radar used in these tests ranged from a minimum of 2.4 to 3 m (8 to 10 ft) in Alabama to about 9 m (30 ft) in Florida. This radar could not detect 0.6 to 0.9-m (2 to 3-ft) diameter vertical pipe cavities in the low loss earth materials characteristic of the sinkhole environment investigated in Florida.

4. The gravity perturbations caused by many underground voids are large enough to be detected using commercially available gravimeters. These voids generally must be fairly large, and located at depths that do not exceed more than about one diameter of a roughly spherical equivalent cavity. This detection capability depends upon the density of the surrounding earth materials and their variations. In practice, a gravity anomaly of about 2×10^{-7} m/s^2 (0.02 milligal) can probably be detected, but this may be the state-of-the-art limit. Normal gravity variations caused by the variations in the subsurface structure are greater than 1×10^{-7} m/s^2 (0.01 milligal). The gravity survey had only marginal success on this program.

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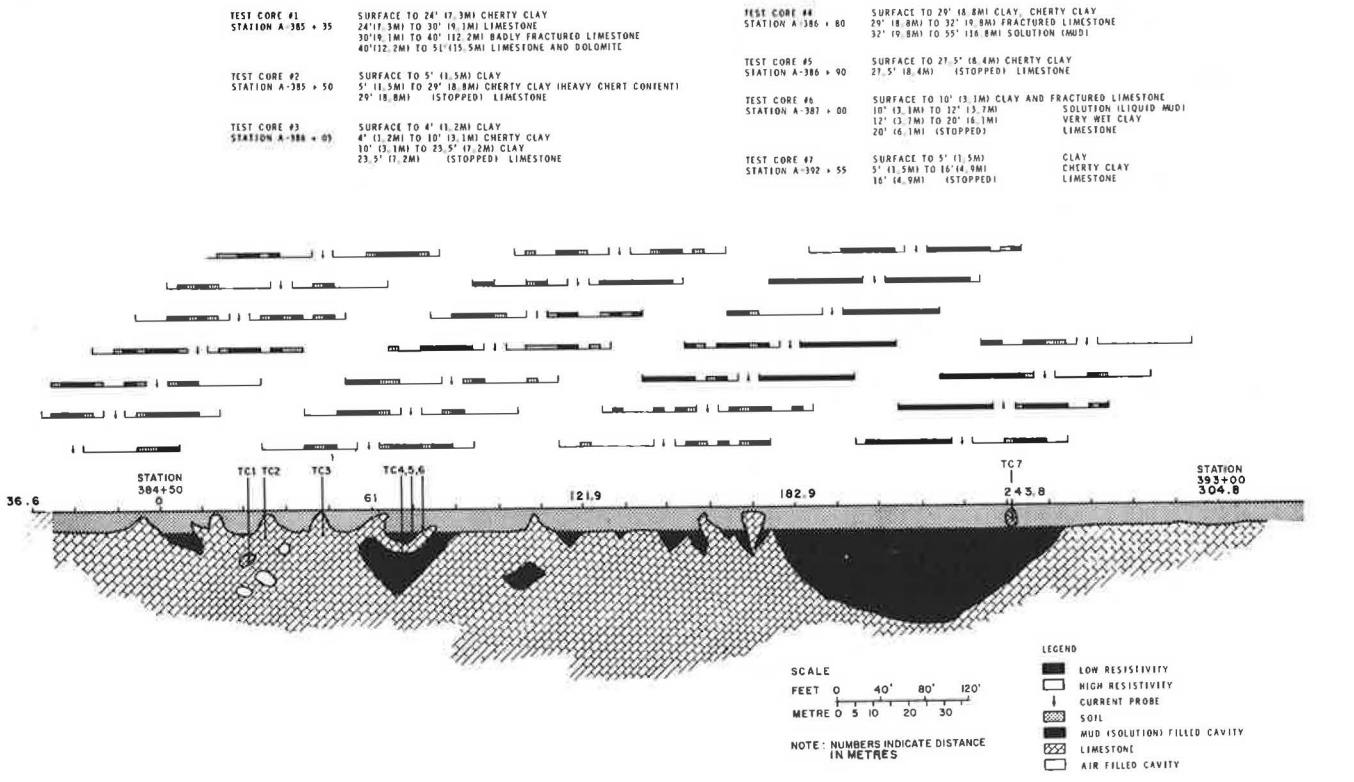
Figure 7. Vertical resistivity profile.



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