IDENTIFICATION AND DELINEATION OF SINKHOLE COLLAPSE HAZARDS IN FLORIDA USING GROUND PENETRATING RADAR AND ELECTRICAL RESISTIVITY IMAGING

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Abstract

Sinkhole development is a geological hazard affecting the northwest quarter of the Florida Peninsula. Government agencies in Florida routinely use geophysics as part of a geotechnical evaluation of sinkholes after a collapse has occurred. Combined with test boring data, ground penetrating radar (GPR) and electrical resistivity imaging (ERI) are important tools for detecting and evaluating the subsurface dimensions of buried depressions, caves, and/or raveling soil pipes associated with ground surface collapse. Three case studies from Florida are described.

Case 1. A 2-inch deep surface depression in Thonatosassa Road east of Tampa was actually the surface expression of a buried sinkhole that had a throat almost 30 feet in diameter as determined by GPR studies. The center of the GPR feature was drilled, raveling soils were identified, and a grouting program was implemented to stabilize the loose soils.

Case 2. A 0.8-foot deep, 25-foot wide surface depression occurred in newly constructed lanes of State Route 54 north of Tampa. Test borings advanced in the center of the surface depression and 20 feet offset showed dense soil to be present. However, a GPR survey showed that the two test borings had been advanced on opposite sides of a 20-foot gap in a subsurface clay layer. A third boring advanced in the center of the gap in the clay layer identified raveling soil. An ERI survey showed that the raveling soil pipe extended to a 40-foot wide dissolution shaft in the limestone.

Case 3. Heavy rains caused an 80-foot wide sinkhole to collapse within a retention basin for Mariner Blvd. The collapse released a torrent of water into cave passages, causing over 40 additional sinkholes in the surrounding area. A GPR survey identified 8 large compound buried depressions beneath a three-block segment of Mariner Boulevard. An ERI survey of the retention basin showed that the large new sinkhole developed along the margin of a large buried depression in the limestone.

These case studies show the important role of GPR and ERI in the evaluation of sinkholes affecting roadways. However, these case studies also draw attention to the fact that geophysical investigations are not routinely performed during the planning of roads and their associated retention basins.

Introduction

Sinkhole development is a geological hazard affecting the northwest quarter of the Florida Peninsula. New sinkhole frequencies are highest in the central and west central areas of the State (Figure 1). New sinkholes form more frequently when both the water table is low and heavy rainfall occurs. With record low water tables after 3 years of drought in the spring of 2001, new sinkholes became a significant geologic hazard in some parts of the State and affected many major roads.

Government agencies in Florida routinely use geophysics as part of a geotechnical evaluation of sinkholes after a collapse has occurred. Ground penetrating radar (GPR) and electrical resistivity imaging (ERI) are important tools for detecting and evaluating the subsurface dimensions of buried depressions, caves, and/or raveling soil pipes associated with ground surface collapse. The images that are provided by these geophysical methods, combined with test boring data, are used to evaluate the volume of the karst feature and to determine the cost

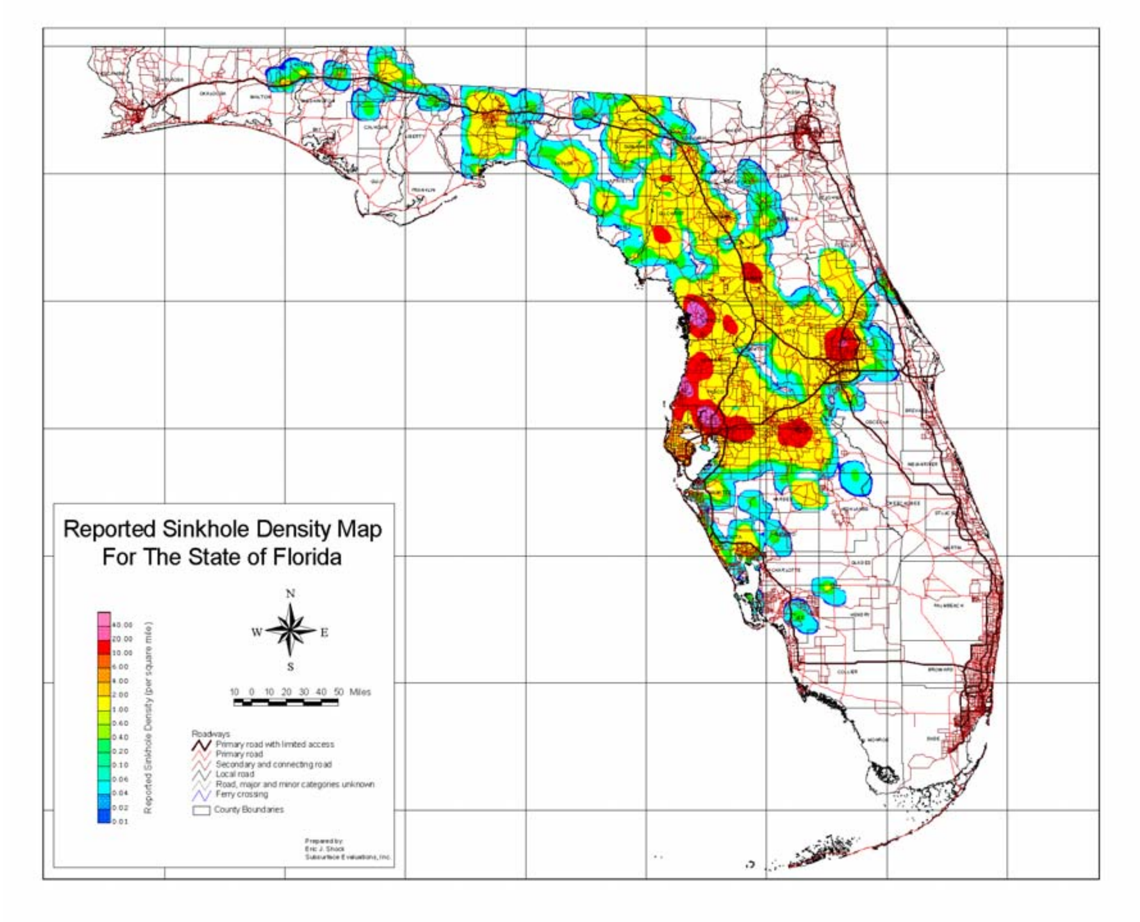


Figure 1: Reported New Sinkhole Density in Florida

effectiveness and best method of remediating the collapse. Three case studies from Florida are described in this paper.

Geophysical Methods

Ground Penetrating Radar

Ground penetrating radar is a noninvasive surface geophysical method used for locating subsurface features and/or investigating the lateral continuity of shallow soil and rock interfaces. It operates by transmitting pulses of ultra-high frequency radio waves (electromagnetic energy) into the ground and then receiving the energy reflected from various objects or relatively sharp contacts between layers of earth materials. A continuous record of subsurface reflections is recorded on a magnetic hard drive as the GPR survey progresses. The GPR signal passes through materials having low electrical conductivities but is rapidly absorbed by earth materials having relatively high electrical conductivity, such as clays, acidic organic soils, and materials saturated with saltwater.

Electromagnetic waves have four components consisting of a positive and negative electric wave and a positive and negative magnetic wave. The electric and magnetic waves are oriented perpendicular to one another. All radar reflections are depicted as three bars representing positive and negative voltages associated with polarity interactions of the electric and magnetic wave couplets at a given interface. The position of the interface corresponds to the top of the middle bar (Figure 2).

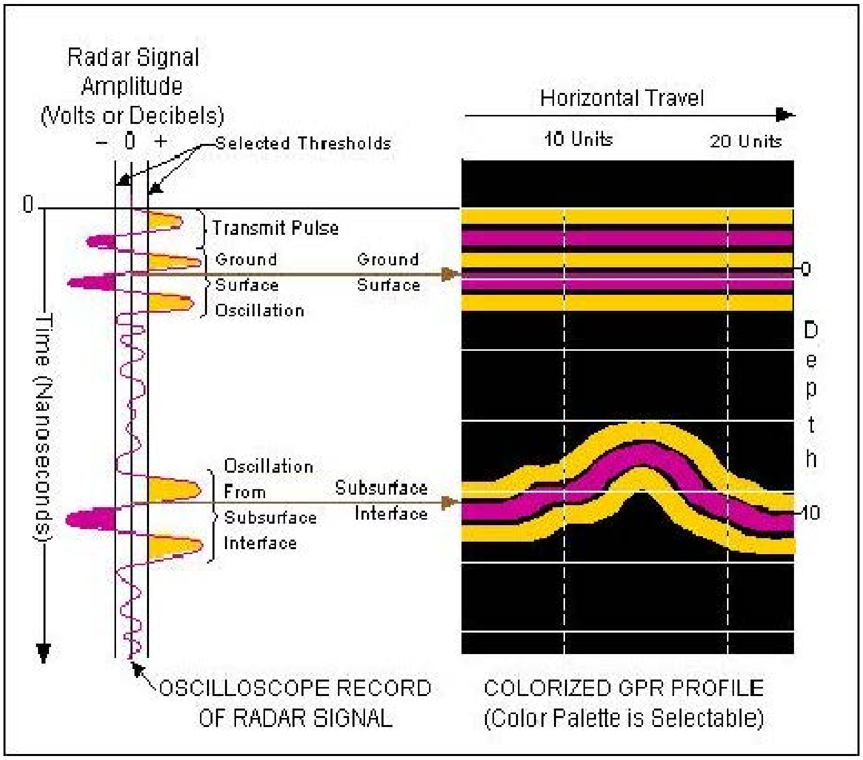


Figure 2: Example of Ground Penetrating Radar Profile

Radar reflections are generated by contrasts in the electrical permittivity (dielectric constant) of the materials through which the electromagnetic wave passes. The electrical permittivity is the capacity of a material to convey electromagnetic waves without absorbing them. Therefore, the radar profile shows the electrical character of the ground rather than density changes. The GPR image is said to depict an "electrostratigraphic" profile. The profile is not a true cross-section because the vertical scale in all layers may not be equal and elevation changes in the ground surface are not depicted. Profiles having these limitations are called "virtual" cross-sections, yet they may be very helpful for documenting the lateral continuity, thickness, and depth of soil, sediment and/or bedrock layers.

The GPR surveys were performed using SIR-2 or SIR-2000 digital control units and antennas with frequencies from 100- to 500-megahertz (MHz) antenna, which are manufactured by Geophysical Survey Systems, Inc., North Salem, New Hampshire. The lower the frequency of the antenna the deeper the signal penetration but the lower the resolution. A 100-MHz antenna has a maximum depth of penetration of about 110 feet in dry sand, a 400-MHz antenna about 38 feet, and a 500-MHz antenna about 30 feet. In practice, the actual depth of scanning is less than maximum because of the presence of shallow silty or clayey soil layers and/or water-saturated soils beneath the area of investigation.

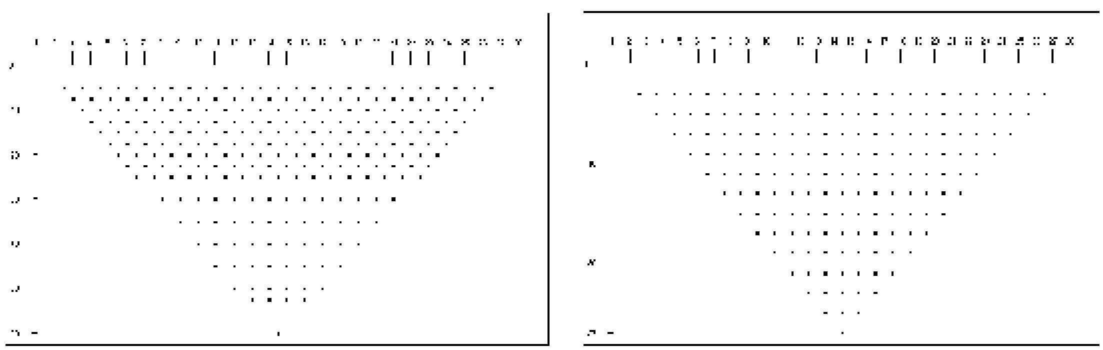
Electrical Resistivity Imaging

ERI is a geophysical method of obtaining a virtual cross-section of subsurface soil and rock layers. It consists of two separate steps: 1) measuring the apparent (weighted average) electrical resistivity of the ground over numerous stations; and 2) computerized processing of the apparent resistivity data to obtain a virtual cross-section of the ground showing the estimated true resistivity values.

In the field, an electric current is passed between two electrodes and the resistivity is measured between a second pair of electrodes. Multiple electrodes and a computerized switching system are used to speed data acquisition. A Sting R1® Memory Earth Resistivity

Meter, a Swift® interface device, a 55 to 70-switch "Smart" cable and 55 to 70 stainless steel electrodes were used to perform the surveys. The equipment was manufactured by Advanced Geosciences, Inc. (AGI), Austin, Texas. It was designed for shallow geotechnical and geological applications and was engineered to have a high signal to noise ratio.

Two electrode arrays are typically used for sinkhole investigations: a dipole-dipole array and a Schlumberger array. A dipole-dipole array places two potential (sensing) electrodes together as a pair, or dipole, separated some distance from another pair, or dipole, of current (transmitting) electrodes. For each successive measurement, the potential electrode pair is moved farther away from the current electrode pair by a distance that is a multiple of the distance between the sensors. The distance between the sensors is commonly called the "a" value. A Schlumberger array consists of two potential (sensing) electrodes in between a pair of current (transmitting) electrodes. For each successive measurement, the current electrodes are moved farther away from the potential electrode pair by a distance that is a multiple of the "a" value. For both arrays, a computerized switching program is used to speed data acquisition. In general, the dipole-dipole array provides better lateral resolution but less depth of penetration compared to the Schlumberger array (Figure 3).



Dipole-Dipole Array Showing Distribution of data points. Depth penetration 15% length of line, good lateral resolution: but loses signal at strength at dept. Provides highest resolution.	Schlumberger Array showing evenly spaced points distribution. Depth penetration 20% length of line. Provides good lateral resolution and good signal strength.

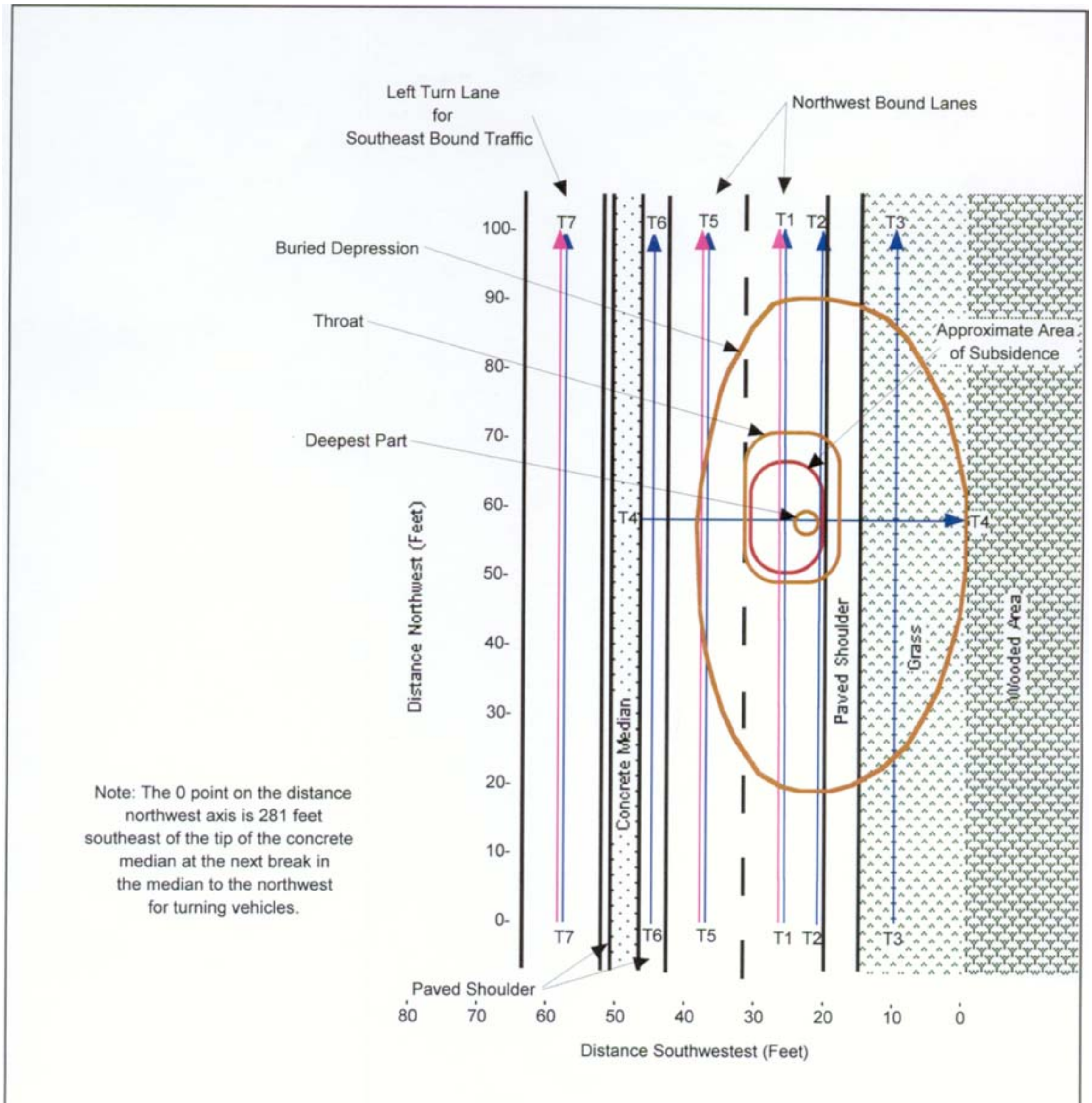
Figure 3: Comparison of Dipole-Dipole and Schlumberger Arrays

A contact resistance test is performed along each transect to test for electrical continuity and for suitable ground resistance before performing resistivity measurements. All contact resistance values should be less than 2,000 Ohms, as recommended by the manufacturer. In cases where the contact resistance exceeds 2,000 Ohms, saltwater is added to the hole to improve (lower) the contact resistance, as recommended by the manufacturer.

Case Studies

Case 1 – Thonotosassa Road

A 2-inch deep surface depression developed in Thonotosassa Road east of Tampa in January 2001. The surface depression was elliptical with a major axis of approximately 16 feet and a minor axis of approximately 12 feet. Prior to repairing the road surface, the Florida Department of Transportation (FDOT) requested that a ground penetrating radar survey be performed as part of the cause-of-subsidence investigation. Seven transects were scanned across and in the vicinity of the surface depression, using 100- and 500-MHz antennas (Figure 4).



Map showing the locations of ground penetrating radar (GPR) transects and geologic feature of interest at Thonotosassa Road south of Interstate 4, Hillsborough County, Florida. The GPR survey was performed by Subsurface Evaluations, Inc. (SEI), on January 17, 2001, using a SIR-2000 control unit and 100-MHz and 500-MHz antennas.

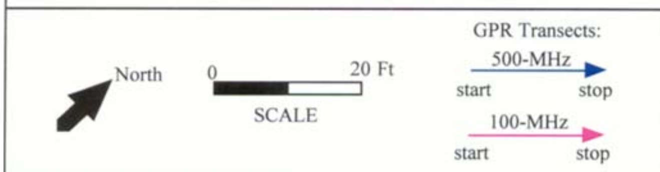
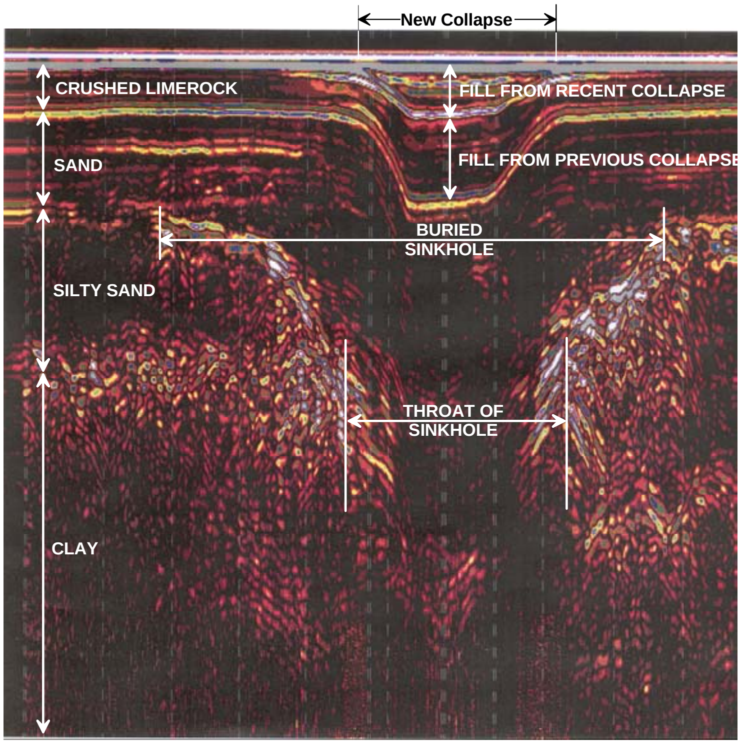


Figure 4. GPR transects and mapped karst features at Thonotosassa Road

Ground Penetrating Radar Survey of Thonotosassa Road Sinkhole, Tampa, FL



Ground penetrating radar (GPR) survey of a newly formed sinkhole in the northbound lane of Thonotosassa Road about 4 miles north of I-4, east of Tampa, Florida. The new sinkhole developed January 00, 2001, and was 00 feet wide. The GPR survey was performed using a SIR-2000 digital control unit and a 500 MHz antenna. Original range was 102 nanoseconds. Surveyed January 00, 2001, by Michael Garman, P.E., P.G., and Scott Waddell, SEI.

Figure 5. GPR profile of the Thonotosassa Road buried sinkhole

The GPR profiles showed a distinct buried sinkhole with a major axis of approximately 70 feet and a minor axis of approximately 40 feet. Within the buried sinkhole there was a 27-foot diameter area where the soil layers were not distinguishable. This area was interpreted as the sinkhole throat containing raveling soil (Figures 4 and 5). The profiles also showed that the road had previously collapsed at the same location and the collapse had been simply backfilled and repaved.

Following the GPR survey, the center of the throat of the feature, as defined by GPR, was drilled. Very loose, very soft, and weight-of-rod sands and clays were found from a depth of 7 feet to a depth of 93 feet. Limestone bedrock was present at a depth of 93 feet. Borings advanced outside the perimeter of the sinkhole showed loose sands and firm to stiff clays. Limestone bedrock was encountered at a depth of 56 feet outside the perimeter of the sinkhole.

When the extent of the GPR feature and the poor soil conditions from the test boring within the throat of the feature were shown to authorities, it was apparent that there was potential for a catastrophic collapse of the road surface. Therefore, a grouting program was implemented to stabilize the loose soils within the throat of the feature.

Case 2 – State Route 54

A 0.8-foot deep, 25-foot wide surface depression developed in newly constructed lanes of State Route 54 north of Tampa in January 2001. Test borings advanced in the center of the surface depression and 20 feet offset showed dense soil to be present. A GPR survey was performed in order to help evaluate the cause of the surface subsidence. Nine transects were scanned across and in the vicinity of the surface depression, using 100- and 500-MHz antennas (Figure 6).

The GPR profiles showed that the two test borings had been advanced on opposite sides of a 20-foot gap in a subsurface clay layer (Figure 7). In addition to the gap in the subsurface clay layer, three other possible buried depressions were identified within the GPR survey area. Based

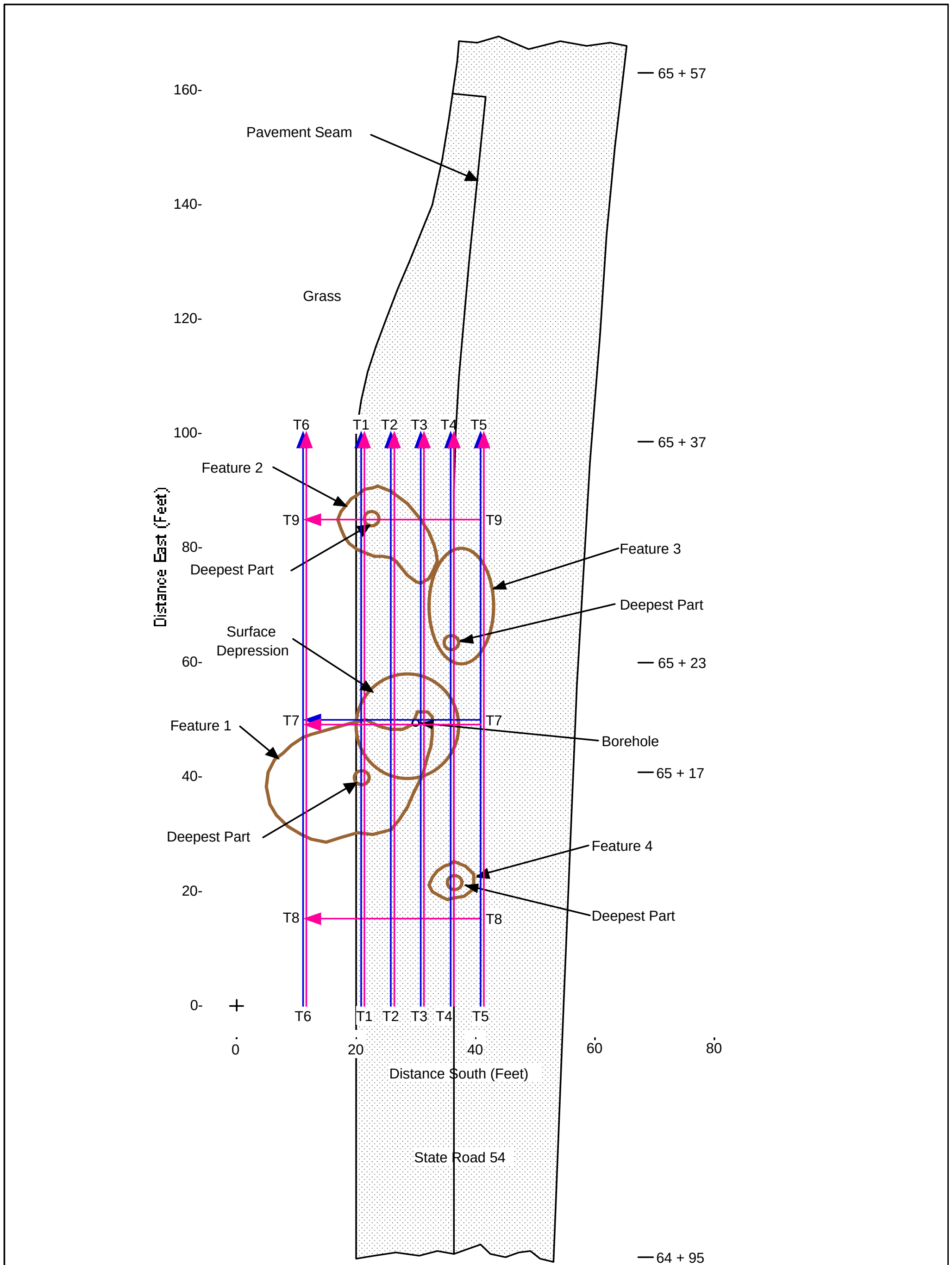


Figure 6. Locations of ground penetrating radar (GPR) transects and features of interest at a new depression along S.R. 54, Land O' Lakes, Florida. The GPR survey was performed by Subsurface Evaluations, Inc. (SEI), on March 13, 2001, using a SIR- 2000 control unit, a 100-MHz antenna, and a 500-MHz antenna.

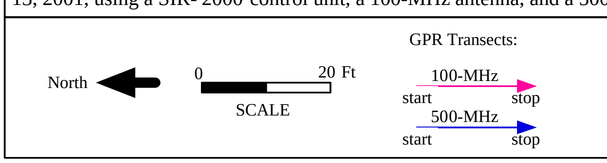


Figure 6: GPR Transects and Mapped Karst Feature at State Route 54

upon the GPR survey data, a third test boring was advanced in the center of the gap in the clay layer. This test boring identified raveling soil.

In an effort to obtain deeper geophysical information, an ERI survey was performed. The ERI survey confirmed the feature identified by GPR and showed that the raveling soil pipe extended down to the edge of a 40-foot wide dissolution shaft in the limestone (Figure 8). After collecting additional test boring data, the decision was made to pave over the depressions. Moving the impacted section of road was not practical and grouting the large and deep subsurface feature was not economical.

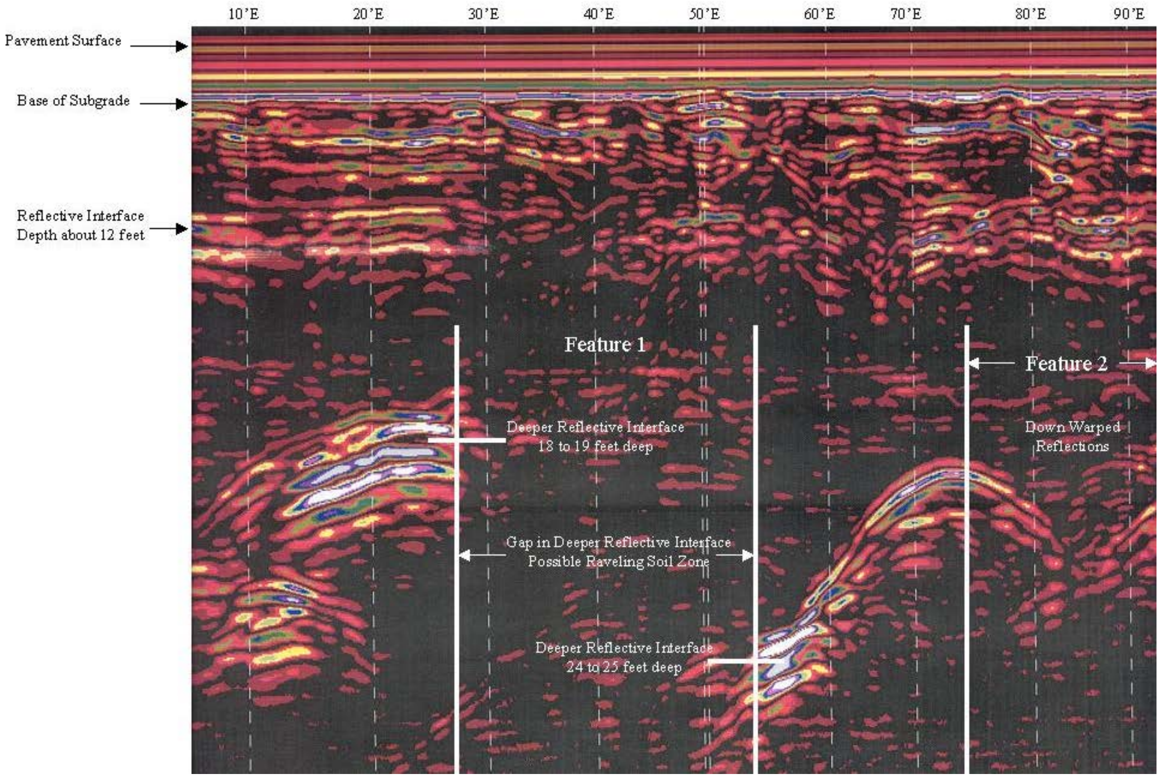


Figure 7: GPR Profile Showing Karst Features beneath State Route 54

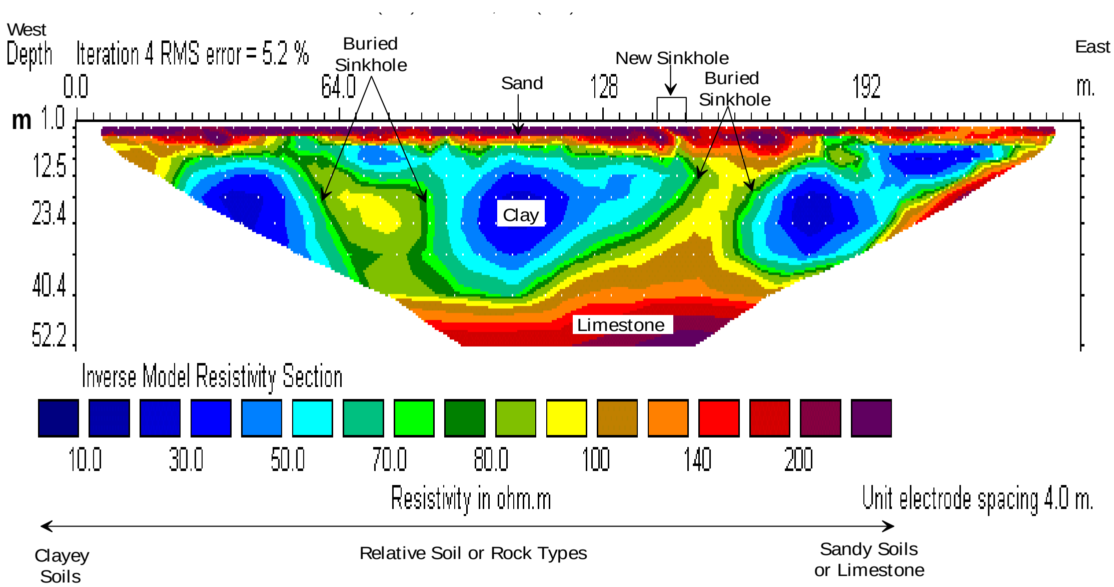


Figure 8: ERI Profile Showing Karst Features beneath State Route 54

Case 3 – Mariner Boulevard

In July 2001, stormwater runoff from heavy rains after three years of drought instantaneously placed several feet of hydraulic head on a retention basin for Mariner Boulevard in Springhill, Florida. The sudden increase in hydraulic head caused an 80-foot wide sinkhole to collapse within the basin. The collapse released a torrent of water into cave passages and caused over 40 additional sinkholes in the basin and surrounding neighborhood. The major thoroughfare, Mariner Boulevard, was affected by several sinkholes and was closed for more than a week while the extent of the sinkhole activity was assessed.

A GPR survey was performed along a three-block section of Mariner Boulevard adjacent to the retention basin. The survey identified approximately eight large buried depressions (Figure 9). These large buried depressions were compound buried depressions as each one contained multiple possible raveling soil pipes. Over 90 possible raveling soil pipes most of which were 5-feet or less in diameter were identified within the eight large buried depressions. Test borings were advanced at the centers of the large buried depressions and loose soil conditions were identified within three of these features.

After the retention basin had been backfilled, a GPR survey was performed within the basin to identify buried depressions that might represent karst features with the potential to collapse if activated by future rainfall events. Seven possible buried depressions were identified within the retention basin (Figure 10). During a subsequent rainfall event, the retention basin filled with water and air bubbles could be seen rising through the water, indicating that there was a cavity beneath the basin. New sinkholes formed within the basin again. After the second failure, an ERI survey of the retention basin was performed to collect deeper information on the subsurface conditions.

The ERI survey showed that the large new sinkhole from the initial collapse had developed along the margin of a large buried depression in the limestone (Figure 11). Higher resistivity material, at depth, was interpreted as representing the top of the limestone bedrock. The top of the possible limestone appeared to dip to greater depths in the west half of the retention basin. SEI inferred that a large depression occurs in the top of the limestone and extends for an unknown distance west of the retention basin. However, the new sinkholes that formed west of Pond B could be mapped as being along the margin of the buried depression in the limestone, which is a commonly observed association. Therefore, SEI inferred that the buried depression in the top of the limestone extended from about the middle of the retention pond to about 100 feet west of Mariner Boulevard and from the middle of the basin southwest as far as Marysville Street. If this hypothesis is true, then the buried depression would be about 300 feet wide, from east to west and about 480 feet from northeast to southwest. Please note that these are inferred dimensions rather than measured.

Because the GPR and ERI surveys identified an abundance of sinkhole precursors, it was economically unfeasible to attempt to stabilize all the features. It appears that the new sinkhole events were triggered by collapses in the retention basin over the large buried depression within the limestone. Such collapses release tremendous amounts of water and pressure waves into the cave tunnels in the limestone, causing soil pipes above dissolution features in the limestone to collapse. Therefore, studies are focusing on methods to stabilize the karst features within the retention basin to prevent future collapses and new sinkhole formation events.

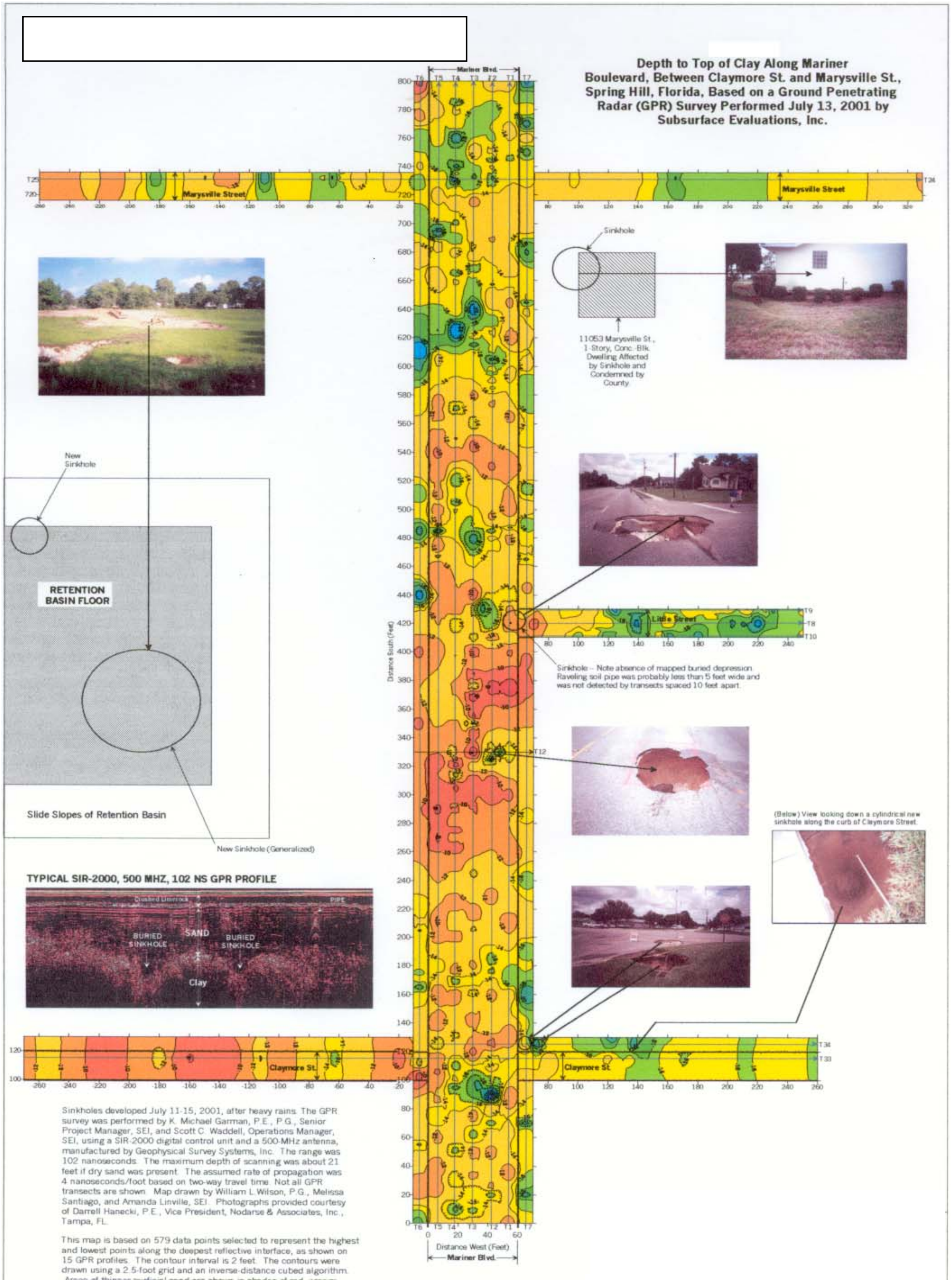


Figure 9. Mariner Boulevard GPR Survey

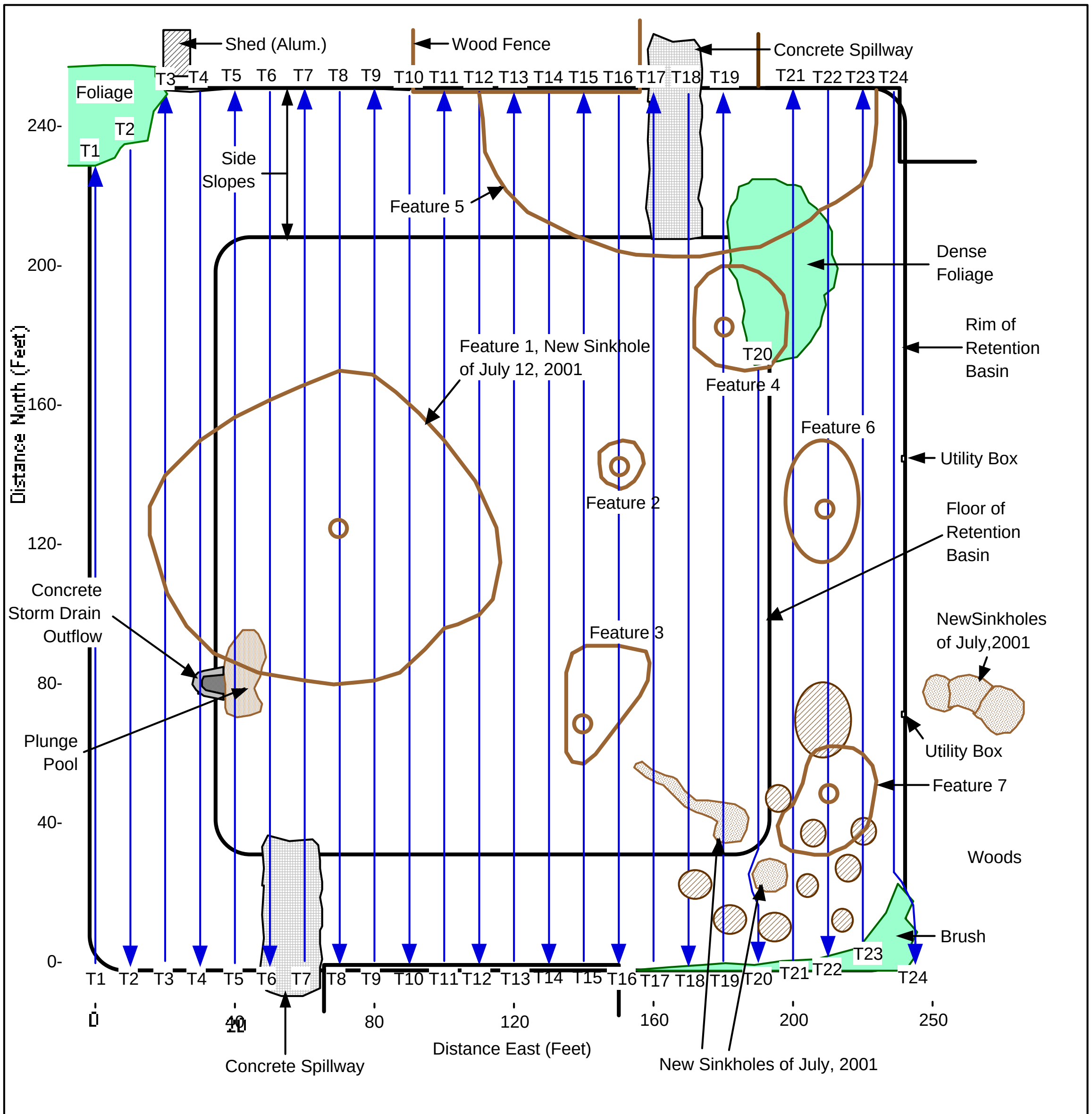


Figure 10. Locations of ground penetrating radar (GPR) transects, buried sand-filled depressions, and new sinkholes as of September 25, 2001, at Retention Basin B, Mariner Blvd., Spring Hill, Florida. The GPR survey was performed by Subsurface Evaluations, Inc. on September 25, 2001 using a SIR-2000 Digital Control Unit and a 400-MHz antenna.

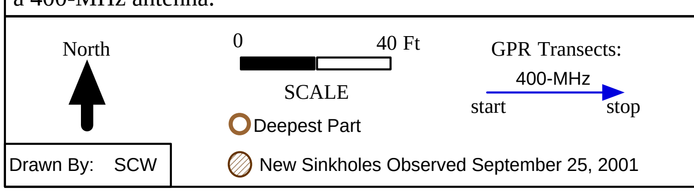


Figure 10: Mariner Boulevard Retention Basin GPR Survey

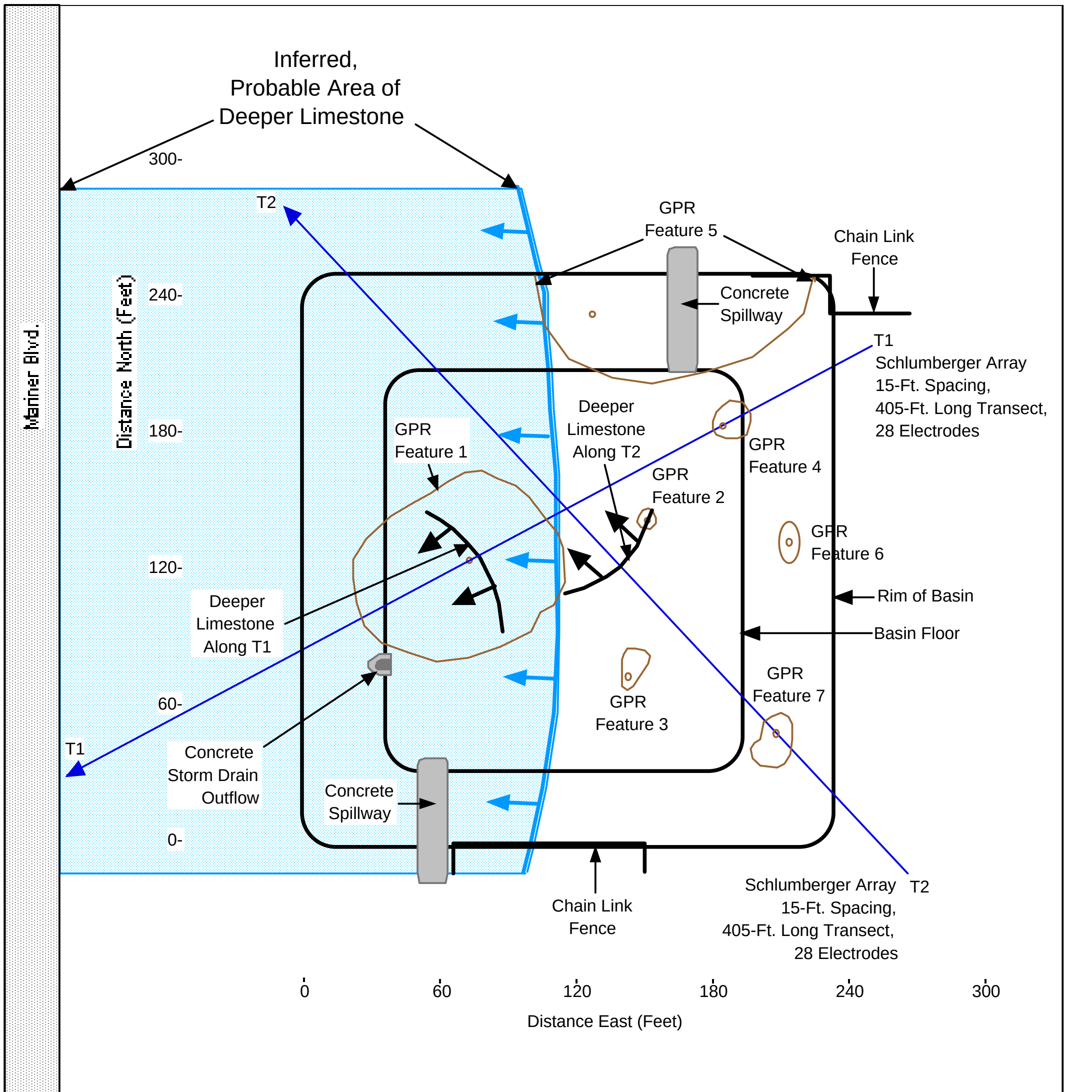


Figure 11. Locations of electrical resistivity imaging (ERI) transects and possible geologic features of interest at Retention Basin B, Mariner Blvd., Spring Hill, Florida. The ERI survey was performed by Subsurface Evaluations, Inc., (SEI) on October 4, 2001, using a Sting R1 Memory Earth Resistivity Meter and a Swift interface device.

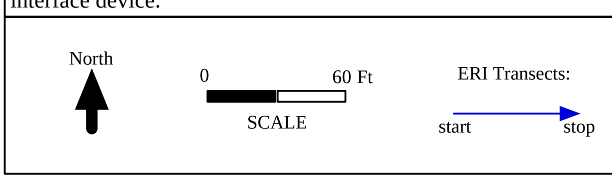


Figure 11: ERI Survey of Mariner Boulevard Retention Basin Summary

Summary

These case studies show the important role of GPR and ERI in the evaluation of sinkholes affecting roadways. On Thonotosassa Road, the GPR survey helped to show that a small surface depression that had previously been paved over was actually an active sinkhole that could cause a catastrophic collapse of the road. On State Route 54, GPR and ERI studies helped to show that the new lanes had been constructed in an active sinkhole area and that frequent repairs would probably be needed. When the surveys were performed it was too late to change the location of the lanes. The Mariner Boulevard GPR and ERI studies showed that the location of the retention basin was over a large buried depression in the limestone in an area with a very high number of subsurface sinkhole precursors. The Mariner Boulevard case demonstrates that retention basin location should not be afterthought in karst areas, but a carefully chosen, geologically appropriate site.

Discussion

These case studies also draw attention to the fact that geophysical investigations are not performed during the planning of roads and their associated retention basins. Sinkhole precursors such as buried depressions, raveling soil pipes, and cavities are readily identifiable by the appropriate geophysical survey. When performed prior to construction, the roads and retention basins can be relocated to avoid adverse conditions or roads can be designed to bridge sinkhole prone locations.

The Thonotosassa Road buried depression could have easily been identified as part of a GPR survey that cost about $10,000.00 to scan in detail (10 miles of road at one transect per lane for four lanes). The road could have been moved to the side approximately 15 feet or built to bridge the 27-foot diameter throat. Instead about $250,000.00 from an emergency budget was spent to stabilize the feature while several lanes of the road were closed.

In the State Route 54 example, the new lanes were located within a sinkhole prone area at the edge of a wetland area. If geophysics had been performed prior to the siting of the road a better route may have been chosen. The present location of the new lanes will require frequent repair work

In the Mariner Boulevard example, an improperly located retention basin caused millions of dollars of damage, including the destruction of several private homes. The buried depressions beneath the retention basin could have been easily identified by a $1,500.00 GPR survey, allowing the retention basin to be moved to another location.