SINKHOLE DETECTION IN FLORIDA USING GPR AND CPT

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Abstract

A portion of Florida's abundant annual precipitation percolates downward through the soil overburden into fissures and cavities in the underlying limestone, often carrying soil with it. This "sinkhole" activity affects transportation facilities, as well as many other public, residential, and commercial structures. To minimize foundation design costs, engineers usually perform a site investigation with only a small number of borings or penetration soundings, and seldom use geophysical methods. The reluctance to use geophysical techniques results partly from the lack of measured engineering properties, and partly from previous negative experience with cumbersome equipment and difficult interpretation. Improved equipment and analysis procedures now provide cost-effective geophysical tools to supplement a site investigation. Many soil profiles in Florida include distinct clay and limestone contacts, which provide good contrast for a Ground Penetrating Radar (GPR) survey. Depressions in these contacts may indicate zones of subsidence, which the engineer can check with Cone Penetrometer Test (CPT) soundings. The CPT provides results superior to Standard Penetration Test (SPT) borings because of better reproducibility and more definitive soil property correlations. Examples illustrate the combined use of CPT soundings and GPR surveys. Both methods are quick, relatively simple to interpret, and essentially non-destructive.

Introduction

Approximately half of Florida has less than 30 m of overburden soil over a thick carbonate (limestone) platform, with rock outcrop in many areas. Often weathered or poorly consolidated near its surface, Florida limestone also contains fissures and solution channels that provide conduits for the vertical flow of surface water into the underlying aquifer(s). Organic and carbonic acids in the surface runoff further dissolve the limestone and enlarge the conduits. This downward movement of water may also transport soils, resulting in ground loss and surface depressions called "sinkholes". Florida's annual precipitation normally exceeds 1.25 m per year and, combined with seasonal fluctuations in groundwater levels; it often accelerates the process of ground loss. In addition, most structures change the surrounding drainage pattern, causing runoff to collect and concentrate in different areas, possibly further accelerating the rate of ground loss. Linear transportation facilities, such as highways, railways, and airports typically traverse a large and variable mass of foundation soils, and thus have even greater exposure to sinkhole activity.

Because of its geomorphology and high precipitation, sinkhole activity in Florida is pervasive and nearly random. For instance, although property insurance policies usually disallow damage caused by ground movement, Florida Statute 627.706 requires that property insurance provided after October 1981 specifically cover sinkhole subsidence. Fortunately, sinkhole depressions usually progress toward the ground surface over a period of many years. Sinkholes generally affect a cylindrical or inverted conical volume of soil extending upward from the limestone "surface", usually an irregular interface with pinnacles, depressions, and holes. They seldom collapse suddenly, are often 10 ft. or less in diameter at the surface, and usually attract little attention unless a populated area is affected. Because of the relatively slow ground loss that occurs within most sinkholes, the structures and facilities built over them often exhibit apparent damage due to differential settlement long before the actual problem becomes readily apparent.

Most engineers would agree that the odds of locating a boring or penetration sounding directly over a sinkhole are slim, especially for site investigations with limited access around an existing structure. Geophysical methods, usually non-destructive and performed from the ground surface, offer a means by which to investigate the soil mass between borings or soundings in a more continuous manner. Usually the soil parameters measured by these methods do not correlate directly with either strength or stiffness, but they do

indicate changes in soil type, water content, layering, and "anomalies" that conventional penetration tests can investigate further. The graphical presentation of results, now common for many geophysical tests, also provides the investigator with intuitive information about site variability.

Although geophysical methods help characterize the soil mass between borings or soundings, ambiguous interpretation and a lack of engineering properties have limited their usage in the past. However, advances in geophysical methods now provide new means by which to investigate for sinkhole activity, often missed during a conventional site exploration program. As a result of better computing power, these advanced methods enhance, but cannot replace, traditional insitu tests. This paper explores the combination of ground penetrating radar (GPR), with the cone penetrometer test (CPT), a reliable and reproducible penetration test.

Site Investigation

The geotechnical engineer designs a foundation based on structural loads and soil stiffness parameters, often with only a few borings or soundings, and normally assuming horizontal layering without lateral variability. For the best accuracy, the designer desires a direct measurement of stiffness, but usually obtains it indirectly through correlation with a strength parameter, such as blow count or penetration resistance. *Figure 1* shows a cube of soil, 30 m (98 ft.) on a side, which might support a 15 m (49 ft.), wide structure. This cube of soil approximates a foundation load spread at 2:1 (vertical: horizontal) to a depth of two times the width of the structure. If the client approves five insitu soundings to investigate the soil within this volume, and each sounding accurately measures the properties of a cylinder of soil 0.3 m (1 ft) in diameter, then the engineer has relatively good information about a volume of soil $= 5 \times \pi(0.3\ \text{m})^2(30\ \text{m}) = 42\ \text{m}^3$, or about 0.16% of the 27,000 m^3 of soil beneath the foundation. Of course, in most design situations, the engineer will probably have only two soundings for this foundation, reducing the volume tested to only 0.06%.

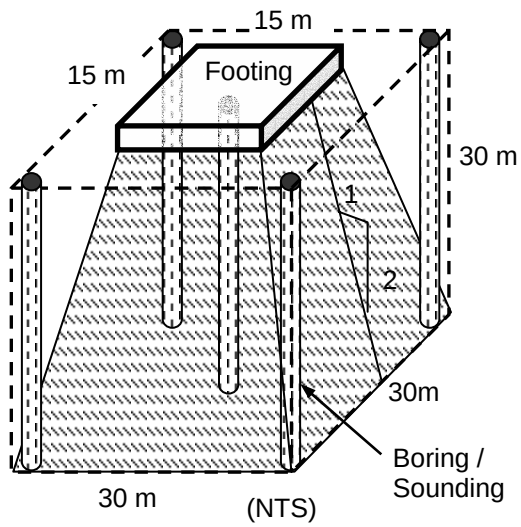

Figure 1: Traditional Site Exploration

In addition, the most widely used exploration method, the Standard Penetration Test (SPT), typically samples only 0.45 m (1.5 ft) out of every 1.5 m (5 ft) penetrated, reducing the actual tested volume by 70%. Furthermore, the ASTM Test Method (D 1586) for the SPT specifies only the hammer drop height and weight, ignoring energy losses that vary considerably between drill rigs. The SPT blowcount varies inversely with the actual driving energy, and may vary as much as 100% (Schmertmann, 1978) with a similar effect on the interpreted soil properties. Investigations based only on lab tests will further reduce the tested volume by more than an order of magnitude.

By comparison, for structural concrete (a manmade material carefully controlled during its preparation, batching, transport, and placement) the Florida Department of Transportation requires sampling and verification testing (slump, air content, test cylinders, etc.) of at least 0.085 m^3 (3 ft^3) for every 38 m^3 (50 yd^3) placed, or about 0.22%. Clearly, the typical site investigation incurs a high risk of poor site characterization, offset only by the optimistic expectation of site uniformity.

Geophysical test methods offer to characterize the soil mass and, although limited in the measurement of engineering properties, can identify "anomalous" conditions between borings or soundings for further exploration. Although separately neither geophysical or penetration tests provide a complete investigation, together they give a more comprehensive view of the foundation subsurface. Regrettably, this combination also increases investigation costs, and testing efficiency and analysis time become important. For reasons described below, the Cone Penetrometer Test and the Ground Penetrating Radar provide an effective combination of complementary methods and reasonable overall expense.

Cone Penetrometer Test (CPT)

The electric CPT specified in ASTM Test Method D 5778 uses strain-gage load cells to measure the tip bearing pressure, q_c, on a 60° conical steel tip with a 35.7 mm diameter, and the side shear developed on a 150 cm^2 sleeve located just behind the tip (*Figures 2 and 3*). The bearing pressure on the tip, q_c, measured on the cross sectional area of 10 cm^2, is a function of the soil's shear strength components (cohesion and friction angle), density, and confining stress. It also correlates with stiffness and past stress history (overconsolidation). The unit side shear, f_s, measured on the friction sleeve mostly helps to identify soil type through comparison with the tip bearing. The friction ratio, $f_r = (f_s/q_c) \times 100\%$, increases in cohesive soils (silt and clay) and decreases in cohesionless soils (sand, shell, and gravel). Normally advanced from a heavy push rig (*Figure 4*) at the standard penetration rate of 2 cm/sec, the CPT provides nearly continuous data (typically every 5 cm of penetration), and has an excellent reputation for repeatability (Lunne, et al., 1997). With the normal thrust limit of about 89 kN (10 tons), a CPT sounding can penetrate 30-100 m of soil, reaching refusal in rock or dense sand/gravel.

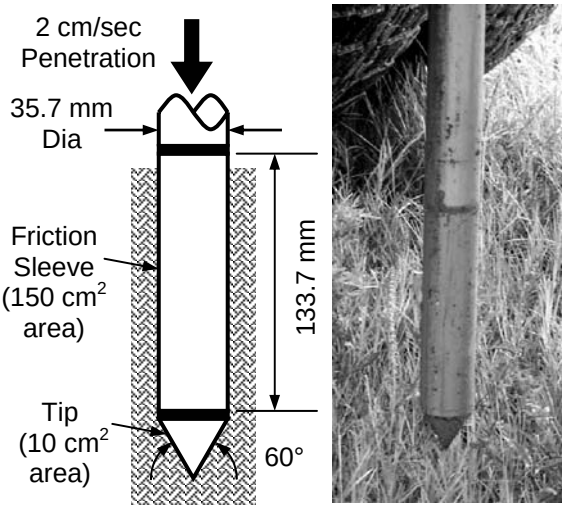

Figure 2: Electronic Cone

Figure 3: CPT Push Rig
(photo Insitu Soil Testing, LC)

Although not standardized, smaller cone tips, advanced by hand, provide similar results in restricted areas adjacent to existing foundations. De Lima and Tumay (1991) concluded that a 12.7 mm diameter cone tip with a 1.27 cm^2 cross-sectional area measures approximately 18% greater tip bearing ($\therefore$ multiply it by an 0.85 correction factor). *Figure 4* shows a hand cone penetrometer (HCPT) with a 1.5 cm^2 cross-sectional tip area. The operator advances the tip in 150 mm increments, recording the maximum tip bearing measured during each increment by a hydraulic pressure gage. The HCPT shown in *Figure 4* has inner rods that advance the tip to minimize friction error along the rod length. With a maximum bearing pressure of 700-1000 kPa, HCPT soundings usually do not exceed a depth of about 3 m (10 ft), depending on the strength of the surface soils. However, in an investigation of suspected sinkhole activity, loose and weak soils may allow much greater penetration depths. This tool also has the unique capability of testing the support condition immediately adjacent to a footing or (after drilling a small hole) under a floor slab.

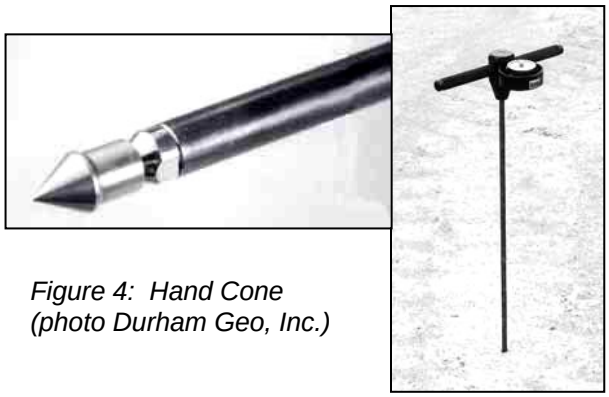

Figure 4: Hand Cone
(photo Durham Geo, Inc.)

Because the CPT reliably differentiates soil stratigraphy and provides a direct measurement of strength, it complements geophysical testing for sinkhole activity very well. Both the CPT and the geophysical test should

clearly show contacts between clay, sand, and limestone layers, and the CPT accurately identifies the loose or weak zones of soil commonly found around a solution feature. SPT borings, sampling at 1.5 m (5 ft) increments do not provide as much information, identify contacts less distinctly, and have reduced sensitivity in weak soils. CPT soundings are also usually quicker than the SPT borings, and do not encourage further ground loss by pumping additional water or drilling mud into the formation. The CPT does not provide a sample for visual inspection, but direct push samplers are available for use with many CPT rigs if desired. Hand augers can also provide near surface samples at depths less than 6 m (20 ft).

Ground Penetrating Radar (GPR)

The GPR relies on the reflection of a high frequency (25-1000 MHz) electromagnetic (EM) pulse from layer contacts and other "anomalies" (boulders, cavities, utilities, tanks, etc.). Most GPR surveys follow a linear path along the ground surface and use the common offset mode of operation, in which a transmitter and receiver are located a fixed distance apart (< 2 m) and pulled together. Following an energy pulse from the transmitter, the GPR device records the magnitude of the reflected energy measured by the receiver over a specified length of time, very similar to reflection seismology that uses much slower sound waves. The velocity and attenuation (loss) of the penetrating EM pulse depend on the electrical properties (dielectric constant and conductivity) of the medium in which it travels. Conductive geomaterials, especially those containing water and salts, interact with and absorb the incident energy, slowing the speed of the pulse and reducing its magnitude (and the potential magnitude of any deeper reflections). Although somewhat focused, like many other wave phenomena, the EM pulse spreads in three dimensions, further reducing the energy available to reflect from a specific contact. A low frequency pulse contains more energy than a high frequency pulse, and it will penetrate farther into the subsurface. However, the resulting longer wavelength also reduces the reflection from a smaller target. Cardimona, et al. (2002) discuss the basic principles of EM transmission in geomaterials in more detail.

Figure 5: 100 MHz GPR Antenna (at Lake Alice Site)

Figure 6: 500 MHz GPR Antenna (at 39th Avenue Site)

Barr (1993) reported positive results using the GPR to identify subsurface karst in Florida. However, GPR surveys performed more than 10 years ago struggled with a number of logistical and instrumentation limits. For this reason, many engineers who may have attempted to use GPR surveys in the past have a poor opinion of their capabilities. Fortunately, the dramatic increase in the power and portability of computer equipment has significantly bettered the capability of the GPR. Modern GPR equipment (see *Figures 5 and 6*) and analysis methods include many technical improvements that warrant a second consideration:

1. *Better antenna design:* focuses the transmitted and reflected energy in a dominant frequency range for isolation of the desired reflection phenomenon.
2. *Fiber optic cables:* between the GPR control unit and the antenna eliminate potential GPR reflections from the cables and electrical noise induced in the cabling by reflected radar energy.

3. *Shielded antennae:* use newer materials that essentially eliminate spurious aboveground reflections (trees, cars, power lines, etc.) and provide a cleaner reflection record.
4. *Improved batteries:* extend fieldwork and eliminate potential electrical noise from generators.
5. *Measuring wheels and hip chains:* provide distance measurement recorded with each wave trace for more accurate location of anomalies.
6. *Satellite GPS information:* recorded with survey traces provides both plan location and elevation to correct survey for surface elevation differences.
7. *Modular equipment and better antenna skids:* improve field efficiency (including multi-channel control units capable of monitoring more than transmitter-receiver combination).
8. *Computer control:* of the equipment offers quick setup and equipment that is more compact.
9. *Digitized waveforms:* can be stacked to reduce noise and stored unaltered in a field computer.
10. *Real-time computer display of data:* using a color palette for reflection intensity and preliminary filters helps identify areas of interest during the fieldwork.
11. *Computer manipulation and display:* of a survey profile allows for the iterative application of different filters and signal enhancement techniques, eliminating the need for multiple field profiles performed with different filters.
12. *Color plots on plain paper:* provide economical presentation of survey profiles.
13. *Improved analysis methods:* provide the potential for inverse and 3-dimensional modeling.
14. *Reduced field effort and cost:* due to the many improvements listed above.

The ability to apply post-survey filters to stacked wave traces stored in a computer, without additional fieldwork, provides a strong benefit to the investigator. Gain and noise filters (frequency, background removal, etc.) allow the engineer to enhance the survey data and identify less obvious subsurface features. These enhancements may even provide subsurface information through clay or brackish water, previously nearly impenetrable using the GPR. Research efforts, such as those presented by Anderson and Cardimona (2002), also continue to advance the understanding of how different subsurface characteristics affect a GPR survey. In summary, GPR survey methods can have a real impact on geotechnical investigation efforts and help to identify subsurface features missed by more conventional and necessarily limited penetration testing techniques.

Effective Combination of GPR and CPT

A GPR survey effectively complements CPT soundings during sinkhole investigations, filling in the untested area between soundings and indicating potential areas of subsurface activity. Because of the deposition process of clay, the surface of a clay layer should be relatively uniform and flat. Therefore, an uneven or dipping sand over clay contact provides a good indicator of potential subsidence. Loose or weak soils may also cause irregular GPR reflections when juxtaposed with undisturbed soils. Abrupt changes in density should show irregular or abnormal reflections, possibly even producing a "bow echo" in the GPR profile near a cavity. Conversely, soil profiles without changes in density, soil type, or layering generally show few irregular or strong reflections, confirming the uniformity of conditions between CPT soundings.

In general, the investigator should perform the GPR survey before any penetration soundings (or borings). CPT soundings, targeted at suspicious zones identified by the GPR, provide both an indication of soil type and a measurement of strength, usable both for foundation design and for identifying zones of subsidence. The nearly continuous CPT sounding information provides a quick and definitive means by which to investigate "anomalies". It also helps adjust the estimate(s) of EM wave velocity. To assign a depth scale to a GPR survey, the investigator must halve the two-way travel time of wave trace and multiply it by the EM velocity, often chosen as an average value of 100 mm/ns. The known depth from the CPT sounding to contacts matched in the GPR survey helps improve the accuracy of the assigned velocity, which may vary in the range of from 50-150 mm/ns as a function soil type, salinity, density, etc. The hand cone penetrometer works best in areas of restricted, specifically near existing foundations. Its small size helps to confirm soil strength immediately adjacent to a footing, or beneath a floor slab through a small hole drilled in the slab.

CPT soundings outside of a zone of ground loss usually show comparatively stronger soils than within it, effectively demonstrating a subsurface hazard to a skeptical client or layperson. Because of its high reproducibility and precision (especially compared to the SPT), the CPT also provides an excellent tool with which to confirm the lateral extent of a subsidence zone. Although the CPT cannot easily penetrate limestone, and therefore cannot find cavities within the limestone formation, it can provide convincing evidence of ground loss effects.

Site Investigation Examples

The following examples illustrate the effective combination of the CPT and the GPR:

UF Lake Alice, Gainesville, FL

In June 2001, a "classroom" field demonstration with the GPR identified a buried sinkhole feature adjacent to Lake Alice on the campus at the University of Florida. Agricultural crop research had tilled and compacted the surface soils over many years, leaving a gentle slope with no discernable surface indications of sinkhole activity. This site has approximately 3 m of dry sand at the surface, underlain by a thin layer of clay, then mixed soils down to a depth of about 20-30 m at the limestone surface. The class assisted in performing ten GPR profiles parallel to the strike of the slope and approximately 30 m long each using a 100 MHz shielded Ramac antenna (*Figure 5*). Several of the GPR profiles indicated a depression of approximately 2 m in the clay surface similar to that shown in *Figure 7*.

Subsequent CPT soundings performed using the UF CPT rig (two shown in *Figure 7*) confirmed the drop of the clay layer and showed very weak clayey sands beneath the depression to a depth of at least 33.5 m. The GPR survey required about an hour of fieldwork, and the three CPT soundings required about 4 hours. Drought conditions in Florida at the time of the survey had desiccated the surface sand layer, and a wave speed of 150 mm/ns provided the best GPR-CPT depth match. The relatively good strength of the sand compacted into the depression (CPT03) indicates minimal subsidence activity at this time, but altered drainage patterns caused by removal of overburden soils for a foundation or drainage pond could quickly reactivate this feature. Although the clay layer significantly reduced GPR reflections below it, a traditional site investigation based only on penetration soundings or borings would likely have missed this clear indication of a "paleosink".

NW 39th Avenue, Gainesville, FL

NW 39th Avenue, a 4-lane state highway (SR222), runs East-West through the northwest quadrant of Gainesville, FL. It intersects a North-South lineament of sinkholes to the West of SR232, which includes the Devil's Millhopper State Park. The section of westbound roadway shown in *Figure 10* has settled approximately 0.4 m along the northern gutter since widening the roadway to four lanes in the 1980's. Near surface clays maintain high, perched groundwater levels in this area, but the water level in many "ponds" in the area rises and falls with a lower phreatic surface in the underlying limestone formation. A pond approximately 4 m north of the edge of pavement and adjacent to the highway depression receives runoff from the surrounding area as well as the roadway.

Nine GPR profiles at this site, 60 m long each, required less than two hours field time. Parallel with the roadway along the north gutter, the median, and the south gutter, the GPR profiles show reflections from the top of the subgrade surface and from a deeper clay layer. The profiles from the 500 MHz antenna (shown in *Figure 6*) provide the best detail in the top 4 m, supplementing deeper surveys obtained with a 100 MHz antenna. The northern 100 MHz profile in *Figure 8* shows two bow echoes at a depth of about 4 m, adjacent to the pond and near the center of the roadway depression. *Figure 9*, from the 500 MHz antenna, shows these two echoes more clearly, as well as the perched ground water above the clay layer, and the surface of the clay dipping downward toward the echoes. Note that the GPR surveys do not include an elevation correction for the surface depression, which will further accentuate the dipping clay layer surface. The hand cone soundings shown in *Figure 8* indicate very weak soil at these bow echoes, but penetration stopped at the 5.5 m depth after using all of the rods brought to the site. A third HCPT sounding near the start of the GPR profiles penetrated only 2.2 m before reaching refusal. An average wave speed of 100 mm/ns provided a reasonable match between the GPR survey and the HCPT soundings. Although somewhat crude by

engineering standards, the HCPT soundings verified a ground loss situation and possible cavities shown by the GPR.

Archer Road, Gainesville, FL

Archer Road (SR 24), in southern Gainesville, crosses shrink-well clay formations that cause problems for many foundations. In addition, the shallow limestone surface, often less than 10 m deep in this area, also heightens the risk of sinkhole activity. Constructed in the early 1980's, the plans for Archer Road called for over-excavating the stiff clay and replacing it with select granular fill to minimize pavement damage due to shrink-swell movement. The 0.1 m depression shown in *Figure 11*, and located along the south edge of pavement of Archer Road near SR 121, appeared several years ago at the beginning of 3-year period of drought in Florida. The depression, though relatively minor, raised immediate sinkhole concerns, and the FDOT performed 15 SPT borings and 5 CPT soundings within an area approximately the size of a football field, extending south from the right lane of the roadway approximately 20 m onto the adjacent right of way. The penetration tests found 1-2 m of surface sand, 10 m of clay, and another 1-2 m of sand, all underlain by limestone. The soundings found little indication of weak soils, seemingly eliminating sinkhole activity.

To further investigate the site, All Coast Engineering recently performed 15 GPR profiles, 50 m long and using both 100 and 500 MHz antennas (requiring about 2 hrs fieldwork). Consistent with the soundings and borings, the GPR profiles shown in *Figures 12 and 13*, located along the south edge of pavement, indicate relatively uniform layering in the subsurface. An average wave speed of 100 mm/ns provided a reasonable match between the GPR survey and the HCPT soundings. Both figures also show an apparent “depression” within the layering that GPR surveys on the right of way did not show, which confirms the overexcavation of the clay within the roadway. The roadway has both a superelevation and a longitudinal grade at this location, and the overexcavation created a subsurface depression in the clay, the low point of which is found beneath the damaged pavement. Surface runoff and groundwater water draining along the clay surface collects in this subsurface depression, causing the clay to swell, beginning during construction. Subsequently the severe Florida drought dried out this zone, causing the clay to shrink and resulting in a small surface depression. The GPR survey in this case found uniform layering at this site and highlighted a construction-related problem instead of a sinkhole.

Summary

1. The typical site investigation based on soundings and borings alone has a significant risk of poor site characterization.
2. GPR surveys supplement traditional site investigations by providing information about stratigraphy between soundings and borings, thus reducing the risk of missing important subsurface features that might affect foundation performance.
3. GPR surveys generally require minimal field effort, and when performed in advance of traditional site investigation, help locate zones of interest to locate borings/soundings.
4. The contrast in properties between clay, sand, and limestone help to identify zones of subsidence. Conversely, a lack of contrast indicates relatively uniform stratigraphy.
5. Although future research should continue to improve the inverse modeling of GPR reflections (possibly including tomography), even a generalized interpretation of each GPR survey provides valuable site information.
6. The CPT confirms zones of weakness and potential sinkhole activity found using the GPR.
7. The CPT helps calibrate the depth scale and determine the GPR EM velocity in the soil at a site.
8. Analysis programs allow the engineer to manipulate raw GPR field data in a computer, removing noise and enhancing reflections, which may attenuate deeper in the profile. False color helps visualize the subsurface stratigraphy and any anomalies.
9. The combination of the GPR and CPT improves site characterization with reasonable expense, especially in investigations for sinkhole activity.

Acknowledgements

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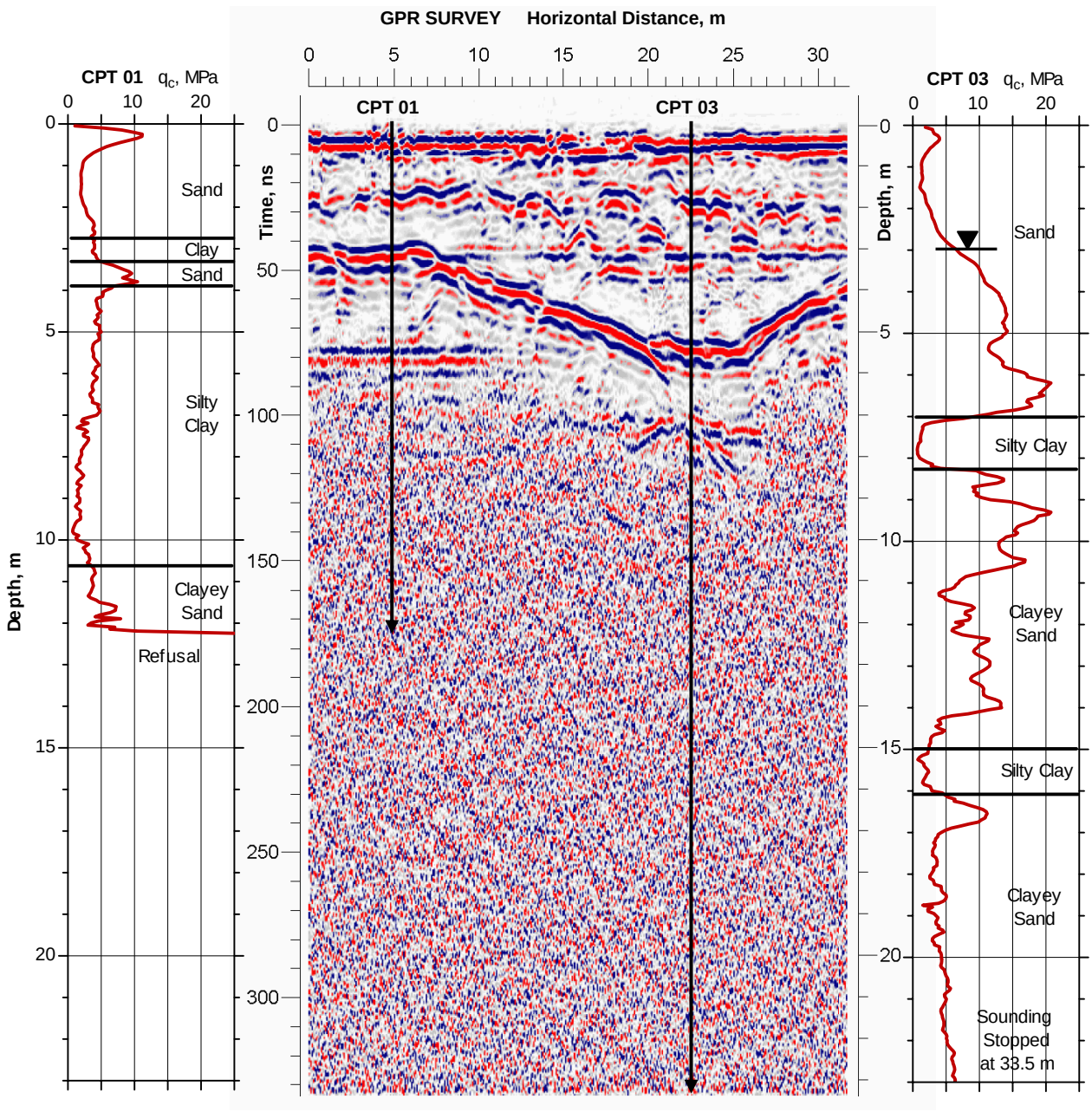

Figure 7: GPR Survey (100 MHz)and CPT Soundings at Lake Alice Anomaly

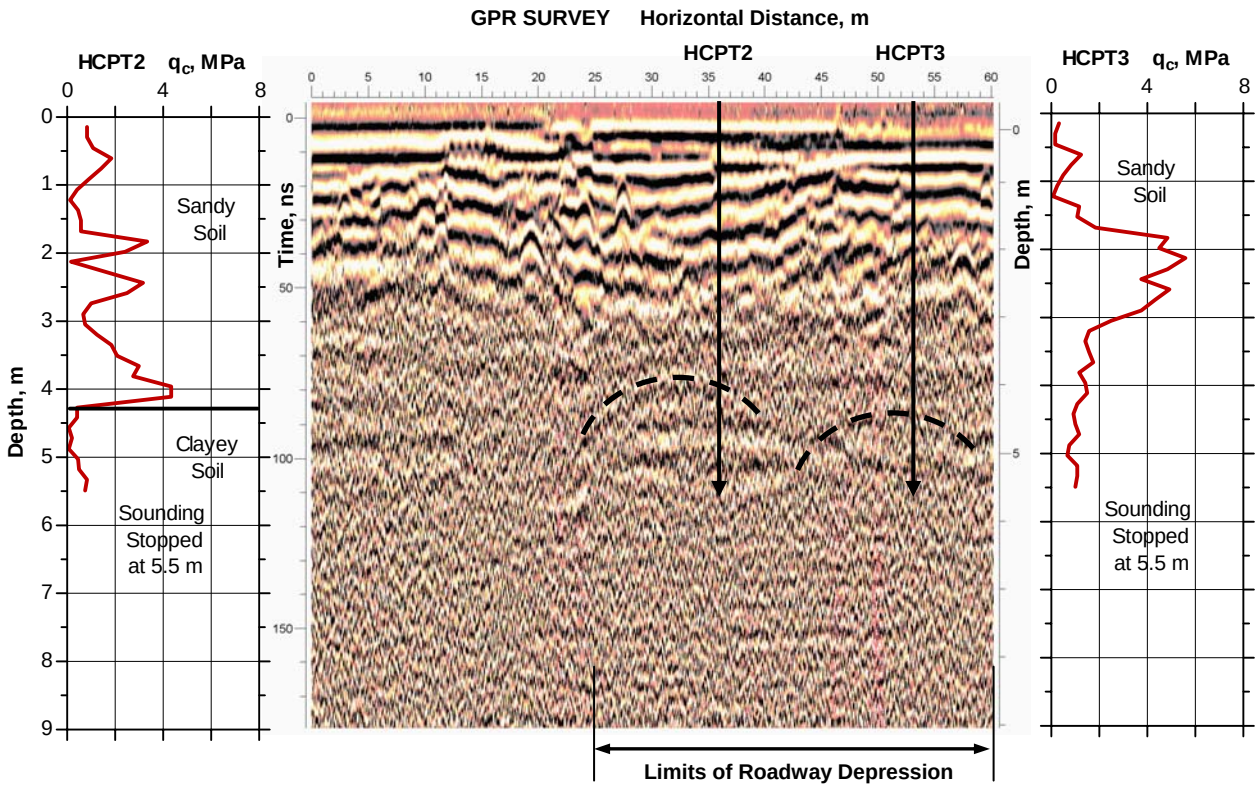

Figure 8 GPR Survey (100 MHz)and CPT Soundings at 39th Avenue Road Anomaly

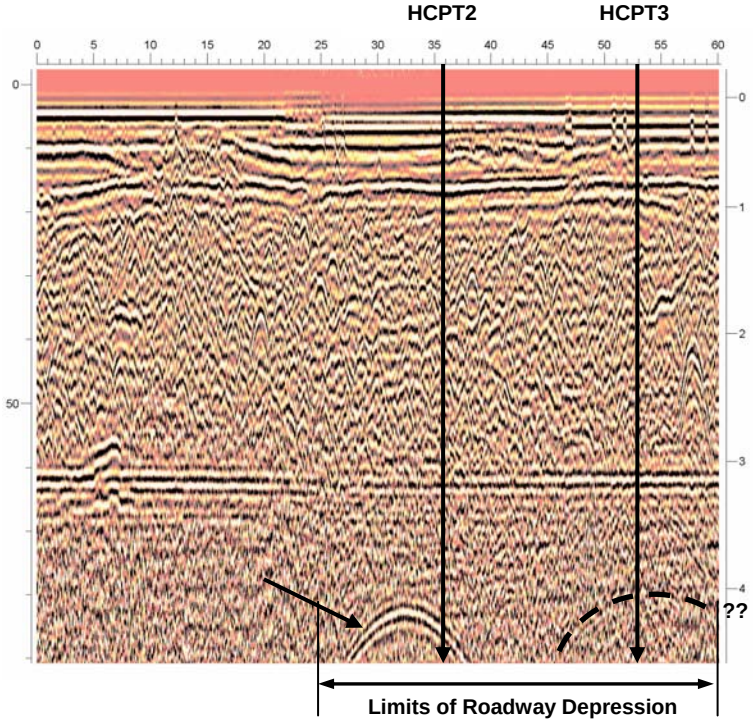

Figure 9 GPR Survey (500 MHz) at 39th Avenue Road Anomaly

Figure 10 Roadway Depression Near 39th Avenue Anomaly

Figure 11 Water Ponding in Depression Near Archer Road Anomaly

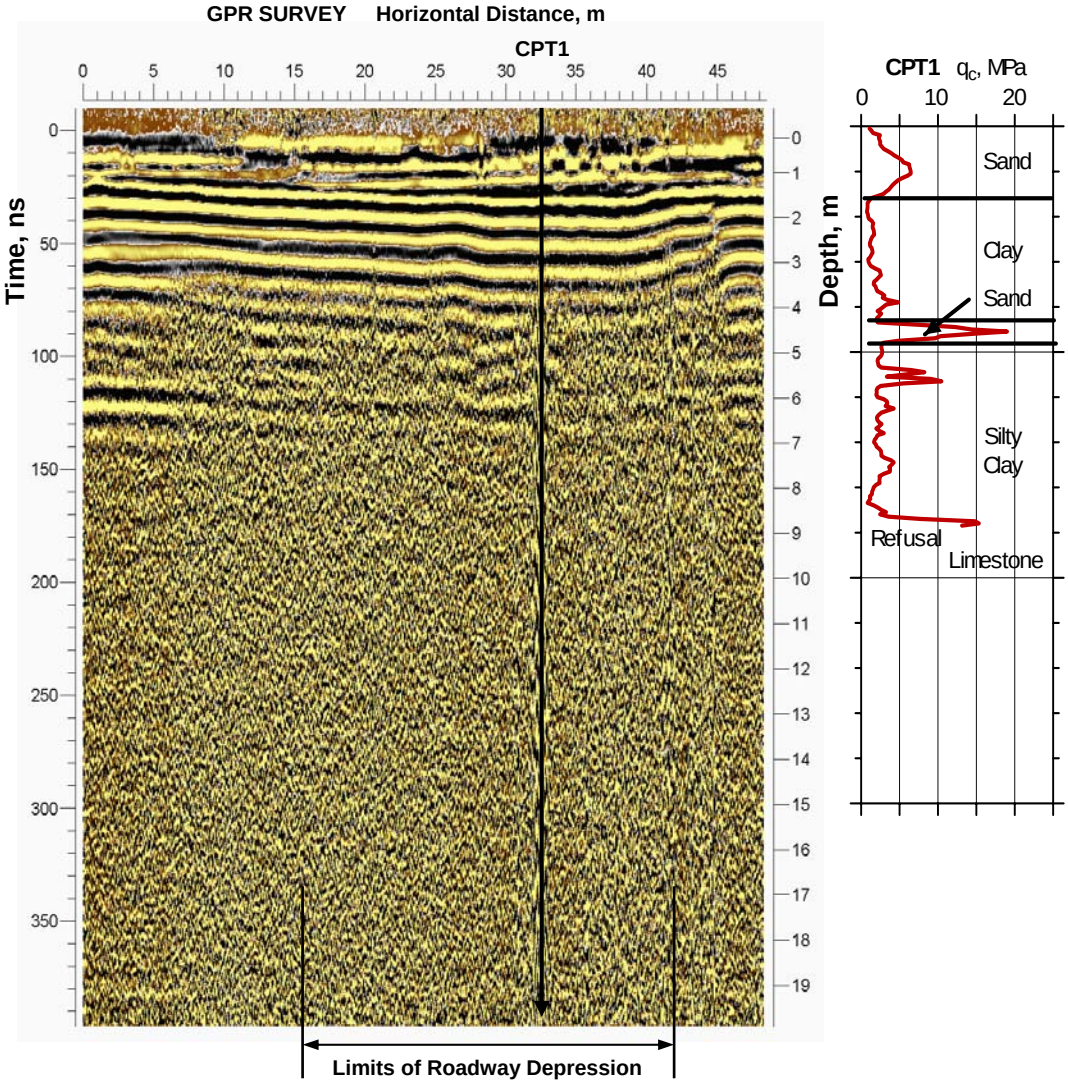

Figure 12 GPR Survey (100 MHz) and HCPT Soundings at Archer Road Anomaly

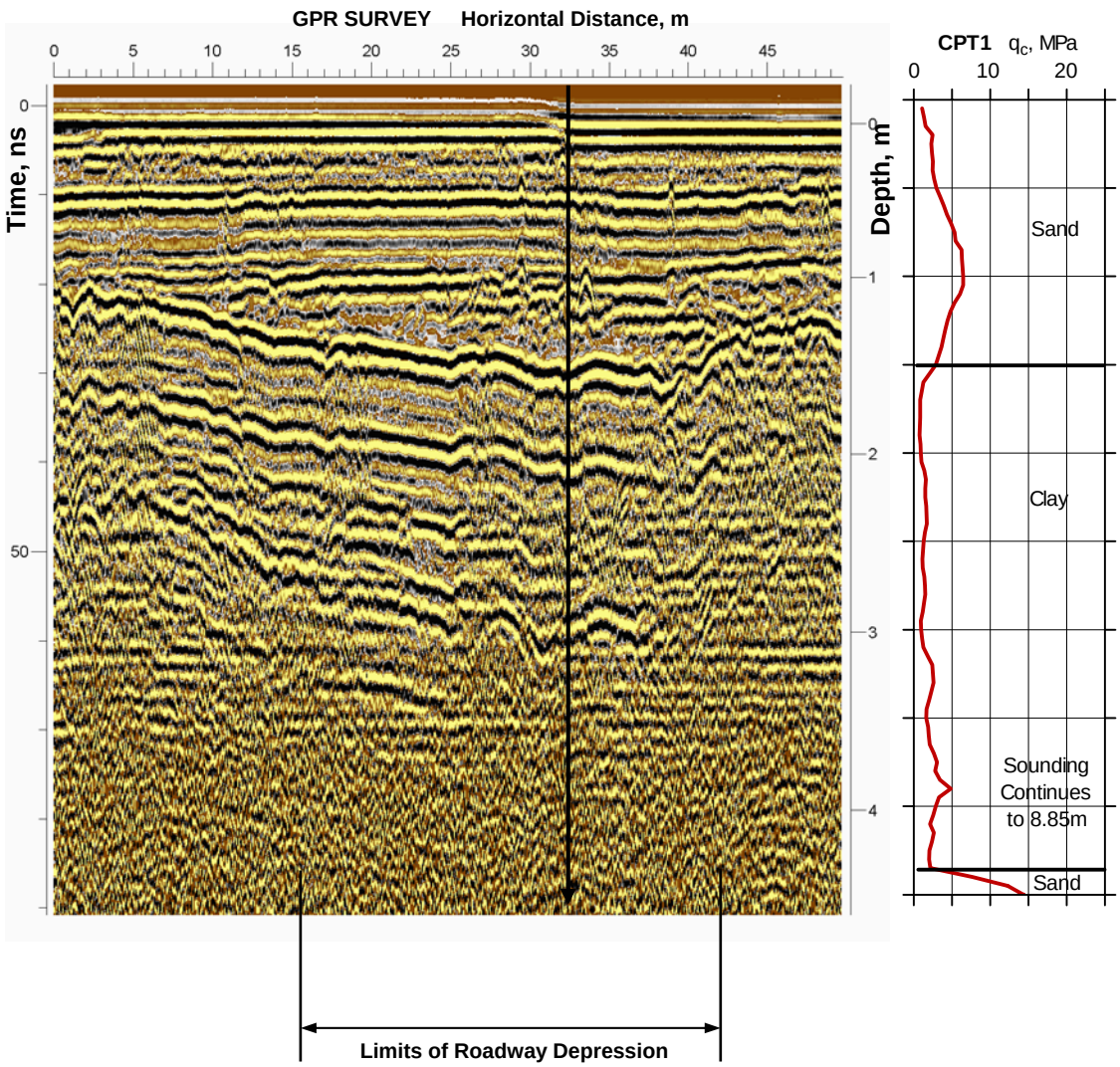

Figure 13 GPR Survey (500 MHz) and HCPT Sounding at Archer Road Anomaly