Use of the Cone Penetration Test for Geotechnical Site Characterization in Clay-Mantled Karst

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Abstract

Adapted for use as a mechanical soil exploration device in the 1930's in Holland, the cone penetrometer has evolved into an electric instrument capable of collecting essentially continuous data in the soil profile in the forms of the tip resistance, pore water pressure and sleeve friction. It provides an essentially continuous profile of information and is capable of identifying abrupt changes in soil stiffness and strength. The production of a typical cone rig makes the level of information comparable to that obtained by geophysical methods, but has the advantages of direct exploration. Although it has advantages over the widely accepted standard penetration test and geophysical methods, the cone penetration test has not been widely used for geotechnical characterization in clay-mantled karst. This paper discusses the relative advantages and disadvantages in the application of the cone penetration test to geotechnical site characterization in karst. It presents cone penetration test data collected at two project sites in deeply weathered, clay-mantled karst of east Tennessee and examines the karst conditions as interpreted from the cone penetration data and the anticipated impact of those conditions on project design and construction.

Geotechnical Characterization in Karst

Geotechnical characterization in karst continues to be a challenge to the engineering community. Subsurface conditions in karst can vary dramatically within a meter either laterally or vertically. The standard penetration test or SPT (ASTM D1586) is commonly used to estimate the relative soil stiffness in the form of the "N-value" as well as collect a disturbed sample. The SPT is performed at discrete intervals and thus may not be representative of abrupt changes in conditions. The rate of conventional auger drilling and performing the SPT depends on several factors, but a production of 30 to 60 lineal meters (approximately 100 to 200 lineal feet) per day per rig is reasonable. Conventional methods for directly exploring below the rock surface include rock coring and air track drilling. While SPT rigs are often equipped to also perform rock coring, the cost per foot is at least three times that of soil drilling which often makes extensive rock coring cost prohibitive. Air track drilling (Weber, 1988) can be a cost-effective option for collecting rock mass information as interpreted by the behavior of the drilling equipment. More detailed discussion of direct exploration techniques for deeply weathered karst is presented by Siegel and Belgeri (1995).

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The use of geophysical methods for geotechnical exploration in karst terrain is well represented in literature. Sowers (1996) summarizes the more common geophysical test methods including gravity and magnetic surveys, ground-penetrating radar, seismic refraction and reflection, and direct wave transmission. With the advent of microcomputers and advanced inversion software, multi-electrode or multi-node resistivity profiling has gained acceptance (Roth, et al., 1999; Kaufmann and Quinif, 2001; Kannan, 2001). The advantage of the geophysical exploration methods is the ability to collect a large amount of data to represent the ground conditions. The disadvantage is that the geophysical data represent force systems in the earth. Thus, such data require interpretation for engineering purposes. The interpretation process and evaluation of significant anomalies are most often aided by complimentary direct exploration and subject to any associated limitations.

Cone Penetration Testing

The cone penetration test (CPT) consists hydraulically pushing an instrumented steel cone into the soil while measuring tip resistance, sleeve friction and pore-water pressure (ASTM D5778). The reference CPT equipment consists of a 60° cone with a 10 cm^2 base area and a 150 cm^2 friction sleeve located above the cone. There are three possible positions for the porous element for pore water pressure measurement: (1) on the cone tip, (2) behind the cone tip, and (3) behind the friction sleeve. The cone can also be equipped with other instrumentation to best suit the scope of the exploration. For karst exploration, the authors have used inclinometers to help identify when the cone is leading off in a near-vertical soil seam in the rock. A comprehensive presentation on the CPT is beyond the scope of this paper and the interested reader is directed to the text *Cone Penetration Testing in Geotechnical Practice* by Lunne et al., (1997). The focus herein is limited to the advantages of the CPT for geotechnical characterization in clay-mantled karst.

The CPT provides an essentially continuous profile of information and is capable of identifying abrupt changes in soil stiffness and strength. Depending on the site and subsurface, daily production for a CPT rig can range from 150 to over 300 lineal meters (about 500 to over 1000 lineal feet). Such production collects a level of information comparable to geophysical methods but has the advantages of direct exploration. The cone is not advanced into rock for two reasons: (1) to prevent damage to the instrumentation and (2) the rock strength usually exceeds the reaction limit. The authors are aware of rotary percussion drilling equipment currently under development that would allow collection of high quality rock information below cone refusal (Applied Research Associates, Inc., 2004; Farrington and Shinn, unpublished; Chitty et al., 2005). However, the collection of information in hard rock is beyond the capabilities of commercial cone rigs at this time.

Site No. 1 – Characterization of the Upper Crust

A five-story hotel was planned for a deeply weathered karst site in west Knoxville, Tennessee, known as the Cedar Bluff area. The initial site exploration consisted of widely spaced borings in which standard penetration testing was performed at regular depth intervals. The test boring data suggested that the near-surface clay was variable and that some of the deeper conditions were consistent with active karst solutioning. Given that the structural system of the hotel consisted of bearing walls with only a few interior columns, grade-supported continuous foundations were expected to represent a cost advantage compared to foundations consisting of pile caps with rock-supported piles. Because the borings were widely spaced and the soil conditions appeared quite variable, a supplemental CPT exploration was performed to better characterize the upper crust.

The CPT data profile shown in Figure 1 was collected at the hotel site during the supplemental exploration. The data consists of corrected cone tip resistance (q_t), pore water pressure measured behind the tip (i.e., the u_2 position), friction ratio (i.e., the sleeve friction divided by the corrected cone tip resistance) and the inclination from vertical in two perpendicular planes. Both q_t and u_2 have been normalized to atmospheric pressure (1 atmosphere = 100 kPa or 2116 psf).

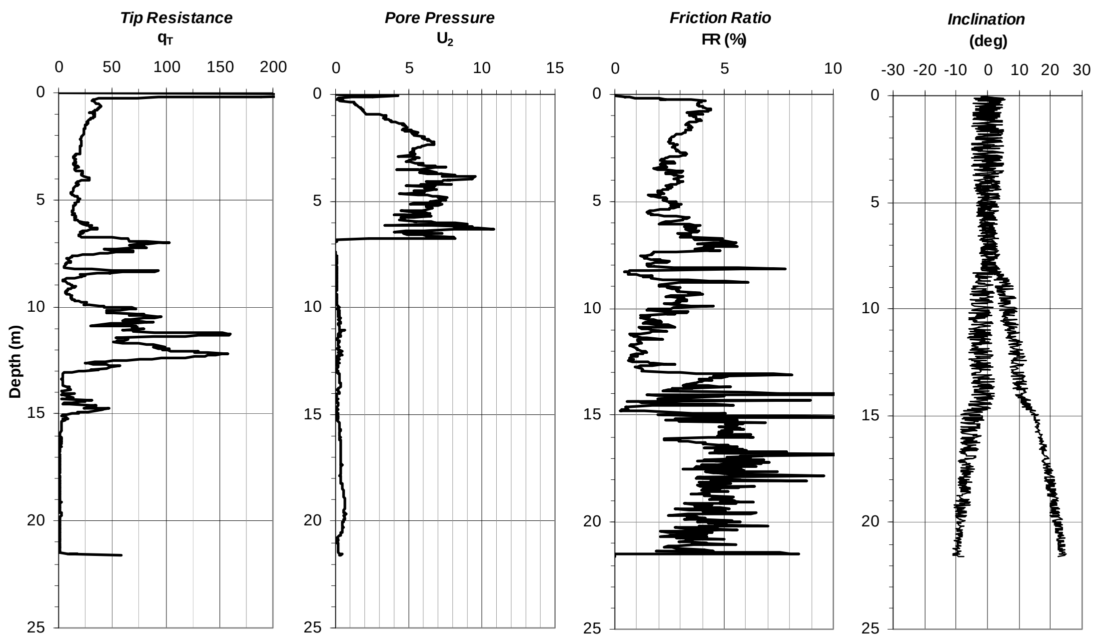

Figure 1. CPT Profile for Example Site No. 1.

Beginning at the ground surface, the CPT profile indicates that the normalized q_t is generally 25 to a depth of 6 m. Between 6 m and 10 m, the normalized q_t is about 10 with some sharp spikes up to 100 and then a substantially stiffer layer (a normalized q_t of 75 or greater) is present from 10 m to 13 m. Below 13 m, the normalized q_t approaches zero until the cone encountered refusal at a depth of approximately 21.5 m. The inclination data shows that cone was displaced from vertical at a depth of about 7 m. Another significant shift in inclination occurred near the depth where the normalized q_t abruptly approaches zero.

The CPT data may be interpreted in light of karst features. As marked in Figure 1, the upper 7 m represents the upper crust and the oldest of the residuum profile. Due to the effects of desiccation, the upper crust is usually moderately over-consolidated with a moisture content near or even lower than its plastic limit. The significantly softer, wetter soils of the soil-rock are immediately beneath the upper crust. The consistency can vary depending on the soil chemistry and stress conditions. Where the soil bridges between two vertical or near-vertical rock pinnacles, the resulting stress concentration leads to consolidation and stiffening. Where shielded from vertical stress and/or influenced by downward migration into openings in the upper rock, the soil is normally or under consolidated and very soft with a moisture content approaching its liquid limit.

From a foundation support perspective, it was concluded that the upper crust was neither sufficiently stiff nor thick enough for support of the rather heavy design loads. While the foundation bearing capacity may have been sufficient, the anticipated compression settlements were beyond the desired limits for the structure. The relatively significant thickness of extremely soft soil below 13 m was interpreted as evidence of extensive karst solutioning and representative of an increased sinkhole risk. It is for these reasons that the structure was designed to be supported by rock-supported micropiles and not spread foundations in the upper soil.

Site No. 2 – Characterization of the Soil-Rock Interface

The subsurface conditions for a proposed six-story medical facility in Knoxville, Tennessee, consisted of a thick clay layer overlying an irregular weathered limestone bedrock surface (S&ME, Inc., 2003; Siegel et al., 2005). As an alternative to a relatively expensive deep foundation system, a combination ground improvement program was developed that consists of: (1) cap grouting the rock surface to significantly reduce the sinkhole risk, and (2) construction of *Geopier*® elements to reinforce and stiffen the soils immediately below shallow foundations. With respect to the former, cap grouting is the injection of low mobilitygrout to fill voids, displace very soft soil and form a barrier at the top of the porous bedrock surface. The initial target areas to receive cap grouting were identified based on extensive cone penetration testing. Figure 2 is one of the CPT profiles collected at the medical center site and it is representative of the general subsurface.

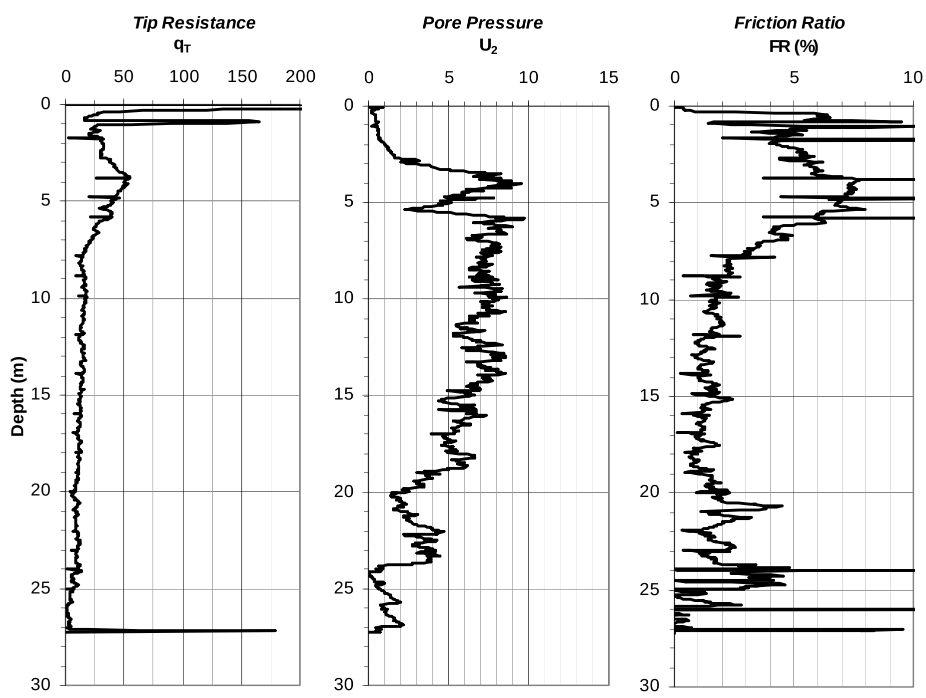

Figure 2. CPT Profile for Example Site No. 2.

The residuum overburden encountered throughout the site ranges from 18 m to 27 m in thickness with a normalized q_t ranging from 10 to 25. A more detailed examination of Figure 2 indicates that the normalized q_t is 25 or greater to a depth of approximately 7 m. Although the normalized q_t gently decreases with increasing depth, it does not approach zero until a depth of approximately 26 m. At the location represented by Figure 2, as well as all other CPT locations, a normalized q_t near zero was interpreted as evidence of karst solutioning and associated downward soil migration. The soft, low consistency soil zones, where present, were typically observed directly above the rock surface and estimated to be 1.5 m to 3 m in thickness. It is these zones of very low corrected tip resistance that were targeted by the cap grouting program. During the field activities for the cap grouting, the program was continuously modified, based on the behavior of the drilling/grouting equipment and interpretations of the CPT data,to insure that engineering goals were achieved. Upon completion of the cap grouting program, the *Geopier*® elements were installed and then conventional spread foundations were constructed at the near-surface.

Reducing Uncertainty

Although not explicitly discussed in the two case histories, the use of the CPT may be considered an effective way to reduce uncertainty for engineering analysis thereby producing more cost-effective solutions. It is a direct exploration technique with a low potential for user-related error, a type of epistemic uncertainty. By collecting a large amount of very detailed information, it may be illustrated that the CPT can help reduce the influence of "natural" or aleatory uncertainty.

For example, often the estimation of the rock surface elevation is important for the design and construction of subsurface structures. For a large underground tank project, a conventional SPT boring exploration provided data at five locations where data for over 30 locations were available from a CPT sounding exploration performed in a comparable timeframe. The coefficient of variation is 1.2% for the former and is substantially less at 0.5% for the latter. Another relevant example involves the determination of the over-consolidated "upper crust" thickness and its ability to develop soil arching as an indication of site stability (Drumm and Yang, 2005). For a two-story office building, three SPT borings are available as compared to 18 CPT soundings. The coefficients of variation for the interpreted crust thickness based on the two exploration techniques are 42% and 26%, respectively.

Concluding Remarks

The two case histories presented herein describe the effectiveness of the CPT in the characterization the soil overburden in clay mantled karst, where the subsurface variations can be extreme. The case histories also illustrate engineering judgment aided by the CPT data and its interpretation. Also illustrated is the advantage of CPT explorations from a statistical perspective as compared to typical SPT explorations.

While it is recognized that most, if not all, geotechnical explorations provide an insufficient amount of data to be *statistically* meaningful, it is emphasized that some techniques will be more effective than others in the application of engineering judgment. Vick's (2002) description of judgment is useful here:

> "Judgment is the means by which evidence is recognized, supporting evidence is compiled, conflicting evidence is reconciled, and evidence of all kinds weighed according to its perceived significance."

So, engineering judgment not only considers the data itself, but also the means of collecting the data, the amount of data, the dependability of the data, and external influences on the data and its collection. Thus, the controlled CPT procedures (and corresponding low potential for user-related error), the essentially continuous profile of measurements that it provides and its capability of rapidly collecting high quality data can help engineers to make better decisions.

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