Combined Measurement of Unknown Foundation Depths and Soil Properties with NDE Methods

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Abstract
This paper discusses a technique for the simultaneous determination of both the depth of unknown bridge foundations and the measurement of soil properties along the length of the unknown foundation. The combined system allows for a more complete and accurate analysis of foundation capacity and scour susceptibility. The foundation depths are measured using the Parallel Seismic testing method, while the soil properties are measured with a seismic cone penetrometer. The new combined technique has a great advantage over previous foundation testing systems in that no borehole is required for either test. Instead, the transducers used to collect all of the required data are mounted together into the same cone probe and pushed into the ground hydraulically from a track-mounted mobile rig. Field testing of the new technique has been carried out, and has shown that the system is capable of quickly and accurately measuring foundation depths and soil properties on a variety of soil types.

INTRODUCTION

The problem of determining unknown foundation depths and unknown soil properties is well-recognized as vital to the evaluation of the safety and performance of existing bridges, as well as in future bridge expansion and rehabilitation. Significant research has been performed towards the research and development of methods for the evaluation of unknown bridge foundations (1,2,3,4), and well-documented methods have been developed in the use of the Cone Penetration Test (CPT) in performing soil characterization (5). Techniques used up to this time, however, have typically separated the functions of foundation length measurement and soil characterization into separate projects carried out by separate teams. In addition, the normal application of the Parallel Seismic (PS) method has been to perform the testing with a transducer in a cased borehole drilled next to the foundation in question. This requirement to have a drilled, cased borehole has been one of the greatest impediments in wider application of this powerful testing method by adding time, cost, and complexity to potential PS test applications

A system has recently been developed and tested which not only combines the foundation and adjacent soil testing into a single function, but also does not require the prior drilling and casing of a borehole for PS testing. The system is referred to as a PS/CPT system, as it combines the functions of a cone penetration test and a Parallel Seismic test into a single system. This system shows great promise in allowing fast, cost-effective determination of foundation depths and soil characteristics at a wide variety of bridge foundation sites. Applications include bridge scour analyses as well as bridge capacity estimation for safety and load upgrading. It is well known that the large number of unknown bridge foundations pose a significant problem to the state departments of transportation (DOT's) because of scour vulnerability concerns. The foundation depth information in particular is needed to perform an accurate scour evaluation at each bridge site, along with as much other information on foundation type, geometry, materials, and subsurface conditions as can be obtained. The recently tested system will allow a large number of soil and foundation characteristics to be measured in a single test.

This paper describes the components and operation of the newly developed system, describes the data which can be obtained from each part of the testing apparatus, and presents case history data showing the CPT data collected from a typical site. In addition, the results are presented of tests comparing the data collected with traditional borehole based PS testing to that obtained from the new system at the same site.

PS/CPT SYSTEM DESCRIPTION

The PS/CPT system is based on a standard system for soil testing which has been modified to allow PS testing in parallel with the soil tests. Soil testing was performed using a Hogentogler 20-ton electronic CPT rig owned by Southern Earth Sciences (SESI) and pictured in Figure 1. The field-testing procedures were performed in general accordance with ASTM Specification D-5778. In the CPT test, an instrumented cone attached to a series of rods is pushed into the soil at a constant rate by a hydraulic cylinder system mounted within the unit. A photograph of the probe being pushed into the soil is presented in Figure 2. Built-in load cells are used to continuously measure the cone tip resistance and sleeve friction resistance that is recorded continuously on a computer. In addition to these values, a porous filter piezo-element located behind the cone tip is used to measure pore pressure during penetration. From the collected data, soil strength and behavior characteristics can be determined over the depth of the CPT sounding.

The soil data, while valuable in itself, is only half of the total picture when evaluating an existing foundation. Measuring the actual depth of the foundation and comparing this to the soils information allows the designer to accurately estimate the in-place capacity of a given foundation. Thus, the standard CPT system was modified to add the capability for PS testing. For the PS/CPT testing, a special seismic piezocone was used to collect the necessary field data. The seismic piezocone incorporates a transducer (geophones or accelerometers) into the body of the cone that is used to record the wave energy from PS test impacts at a series of depths throughout the insertion of the cone probe. A brief description of the PS test method, using both a standard cased borehole and as applied in the PS/CPT system, is included below.

PARALLEL SEISMIC NDE METHOD

The Parallel Seismic (PS) test consists of impacting the exposed foundation substructure either vertically or horizontally with an impulse hammer to generate compression or flexural waves which travel down the foundation and are transmitted into the surrounding soil as shown in Figure 3. The emitted compression (or shear) wave arrival has normally been tracked at regular depth intervals by either a hydrophone receiver suspended in a water-filled cased borehole or by a clamped three-component geophone receiver in a wet or dry cased borehole. The new system uses a geophone mounted into the cone of the CPT unit which is pushed into the soil, and therefore does not require casing or pre-drilling. The coupling of acoustic energy from the soil to transducer is very good due to the intimate contact between the soil and cone probe during insertion.

In a PS test using any type of system, the depth of a foundation is typically indicated by a weaker and slower signal arrivals below the tip of the foundation. Diffraction of wave energy from the foundation bottom has also been found to be indicative of its depth in PS tests as well. The PS test was found to the most accurate and widely applicable NDE method for determination of unknown bridge foundation depths of all tested NDE methods in NCHRP 21-5 research (1,2,3). Other research at Northwest University National Geotechnical Site (NGS) has also indicated that the PS method is effective in measuring foundation lengths of inaccessible piles, although this research also pointed out that some care must be taken when using the method under certain soil/rock interface depth versus pile length conditions (4).

Required Parallel Seismic Test Equipment

When a PS test is performed, either using a borehole or the PS/CPT system, it is required to record the impact force and the responses of the receivers. The equipment needed to perform the data collection includes:

1. Digital signal analyzer or PC based data acquisition system with a sampling rate of at least 100 kiloHertz (10 microseconds/12 bit digital data point) on at least 2 channels (4 channels needed for triaxial geophone) with at least 4096 data points per channel,

2. Signal amplifier(s) for receiver(s) or. (The signal amplification on the PS/CPT system is done down-hole to minimize noise and interference),

3. Instrumented impulse hammers weighing 1.4 to 5.5 kg (3 to 12 lb) to measure impact force and trigger data acquisition upon impact,

4. Hydrophone or triaxial geophone receivers are also required for borehole-based PS tests.

Parallel Seismic Data Interpretation

The main objective of Parallel Seismic tests is to determine the depth of the unknown foundations. Based on the NCHRP 21-5 and 21-5 (1,2) research results, several criteria were established for determining the foundation depths based on Parallel Seismic data as follows:

1. Breaks in the slope of the lines in a plot of depth versus recorded time,
2. Drop in energy amplitude below the bottom of the foundation, and
3. Diffraction of wave energy at the bottom of the foundation.

Examination of Figure 3 shows the case where subsurface conditions are uniform with depth (this usually means saturated soil conditions where the compression wave velocity is that of water, i.e. about 1500 m/s or 4900 ft/s). This allows one to determine the velocity of the foundation element, and to clearly see the foundation bottom as the point where the wave velocity is slower and the amplitude is weaker. The foundation bottom is then taken as the intersection of the foundation velocity line with the soil velocity line as shown in Fig. 3.

PS/CPT Test Considerations

For successful use of the PS/CPT system, there are several considerations which must be taken into account at each proposed testing site.

1. The most effective PS testing is done when the transducer is located as close as possible to the foundation under test. Typically, the borehole to foundation distance should be 10 feet (3 m) or less for the highest quality data. This requirement is to reduce the effect of the surrounding soil, particularly at sites with unsaturated soil conditions. Where saturated soil conditions exist, PS tests have been successfully performed with larger horizontal offsets from foundation edges. The CPT rig used for the new system allows the probe to be pushed into the soil at locations as close as 5-7 feet from the foundation edge, depending on access conditions

2. Ideally, the borehole (for traditional PS tests) or probe penetration depth (for PS/CPT tests) should extend at least 4.5 m (15 ft) below the minimum required foundation depth (from a capacity/scour perspective considering the subsurface geology) or suspected foundation depth, whichever is greater. This requirement is to ensure that data is collected to the depth of interest. If the borehole or probe is not at least somewhat deeper than the foundation bottom, one may only be able to determine that the foundation is at least as deep as the borehole or probe at the maximum depth (unless a foundation bottom diffraction event is recorded). Note that with the new system, it is possible to monitor the data from the PS tests as well as soil conditions from CPT data as the probe is gradually inserted deeper into the soil. Thus, the bottom depth of the foundation can be determined during the course of the testing. This allows the early termination of testing if the foundation is found to be shallower than expected, or, conversely, allows the operator to continue testing until the bottom depth is seen if the foundation is deeper than expected.

3. Site soil conditions must be suitable for testing with a CPT system. Thus, sites with shallow rock or boulders are not generally suited to this type of testing. In addition, the testing cannot be extended into the bedrock for sites with shallow bedrock or sites where the piles bear into bedrock. Thus, this system is most suited for testing driven piles or other foundations placed into relatively soft soils.

PS/CPT VERSUS STANDARD BOREHOLE PS TEST DATA

A series of tests was conducted in the field to compare the performance of the cone-probe mounted PS transducer to that of a conventional PS test using a hydrophone in a cased borehole. The tests were conducted around Mobile, Alabama on existing foundations of concrete, steel, and wood. The results from all tests showed good results, with the results of the tests on a concrete driven pile reported herein.

The concrete pile tested was part of the foundation system for a recently constructed bridge along I-65 near Mobile. All piles for this bridge had well-defined embedded depths, which allowed for comparison to the field test results. A true blind test was not conducted for this investigation, as the purpose of the testing was to compare the cone probe PS results to conventional PS test results under known conditions. The pile ultimately selected for testing was 30-inches square precast concrete at the edge of the bridge. According to installation records provided by the Alabama DOT, the pile had an embedded depth of 54 feet.

The PS/CPT rig was driven to the site, and positioned. The initial pile selected for testing was located several piles in from the bridge edge. However, the attempt to push the probe into the soil terminated at a few feet below grade due to subsurface obstructions. After several unsuccessful attempts to push the probe in at locations nearby, it was determined that the water channel under the bridge was likely lined with rip-rap or a similar material under a layer of soil, which the probe could not penetrate. The final selected probe location was selected outside the bridge, with the probe inserted about 10-14 feet from the tested pile. At this location, the probe was successfully inserted to a depth of 68 feet (20.7 m), which is well below the pile depth of 54 feet (16.5 m). The lateral spacing from pile to probe was larger than desired, but still resulted in very usable, clear data. During the probe insertion, CPT data was collected continuously, while PS tests were conducted at 2 feet (0.2 m) intervals. For each PS test, the pile was impacted 4-5 times with a three pound instrumented hammer, and the response of the transducer in the probe collected with an Olson Instruments Freedom data PC. Both the hammer signal and the receiver response were recorded to allow the travel time to be measured at each depth.

After the cone probe reached the maximum planned insertion depth, it was withdrawn and replaced with a slightly larger diameter sacrificial probe mounted to hollow steel casing. The steel casing was then pressed into the ground at the same location, until the maximum depth was reached. A 1.0 inch (2.54 cm) I.D. PVC pipe was then inserted into the steel casing and filled with water. Finally, the sacrificial cone probe tip was released and the steel casing withdrawn. This resulted in a water-filled, cased borehole located in the exact same location as that used for the PS/CPT tests. A full conventional PS test set was then collected in the PVC pipe using as a receiver a 0.8 inch (2 cm) diameter hydrophone lowered into the casing. Tests were again conducted at 2 feet (0.2 m) intervals.

The results of the tests showed that both set of tests resulted in clear, usable PS data. The results from the PS/CPT test, which used the cone-mounted vertical geophone as a receiver, are presented in Fig. 4. As seen in the figure, the wave energy arrivals at all depths are clear, which a constant move-out versus depth as expected for a typical PS test result. The inflection point in the data corresponding to the bottom depth is visible at about 54 feet (16.5 m), with slower velocity energy arrivals below that depth. The results of the conventional PS test, using a hydrophone receiver in a borehole, is presented in Figure 5. Again, the data is clear and consistent, with the bottom depth inflection point apparent at about 54 feet (16.5 m). The corresponding soils data from the CPT sounding is presented in Figure 6.

Based on experience with PS testing on real-world foundations as well as research into the method, typical PS accuracies are 5% for predicting bottom depths, although situations where the inflection point is difficult to see can result in accuracies of closer to 10% of actual tip depths. The accuracy of the method is greatest for sites with homogenous soil profiles, especially in the area around the shaft tip depth. Accuracy can also be improved by keeping the borehole as close as possible to the foundation element, and by extending the borehole at least 5m (15 ft) below the tip depth. Finally, the clearest and most reliable results are produced by using a relatively high frequency source (such as a steel sledge or instrumented hammer with a hard tip) coupled with a sample rate of 10-20 microseconds per point. This allows the acquisition of higher frequency wave components. This improves accuracy by allowing for lower inherent error in the picking of arrival times for the downhole waveforms.

CONCLUSIONS

The PS test method has been found in previous research to be the most accurate and versatile method for unknown foundation length determination. One major drawback to this method has been the requirement for drilling a cased borehole at each test location. The newly developed combined PS/CPT system allowed the collection of both soil data and PS foundation length data with the ease of a simple CPT test. The ability to collect PS data with quality similar to that of a conventional borehole PS test but without the normal borehole should allow a much wider use of PS testing for unknown foundation length determination for the many sites where CPT testing is possible. Conversely, the ability to collect foundation length data while determining soil conditions using a standard CPT test will result in better assessments of overall foundation capacity and thus improved safety and reliability.

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List of Figures:

Figure 1 PS/CPT Rig On-Station at I-65 Test Site

Figure 2 PS/CPT Probe Being Pushed Into Soil at I-65 Test Site

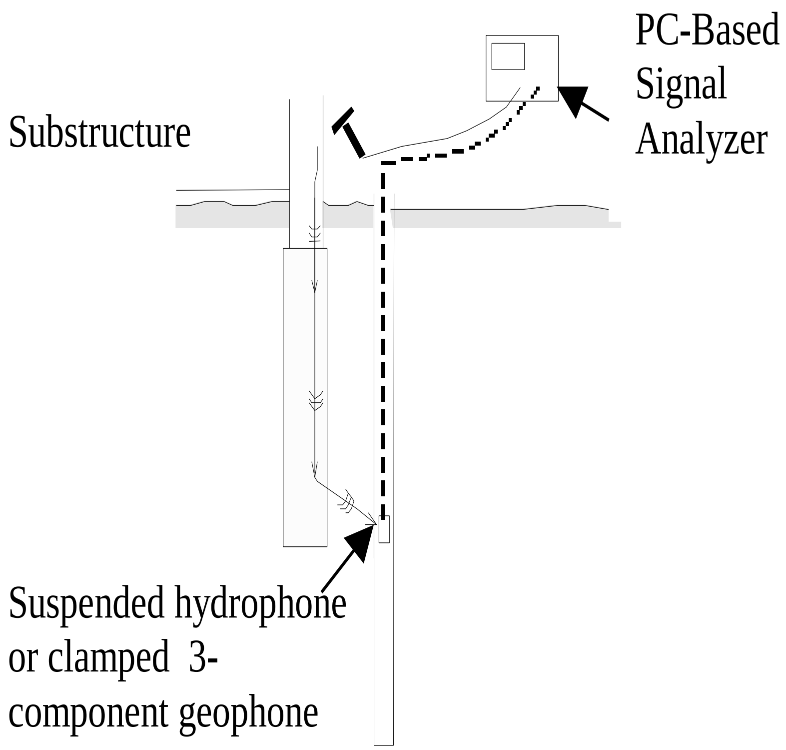

Figure 3. Traditional Borehole-Based Parallel Seismic Method Diagram

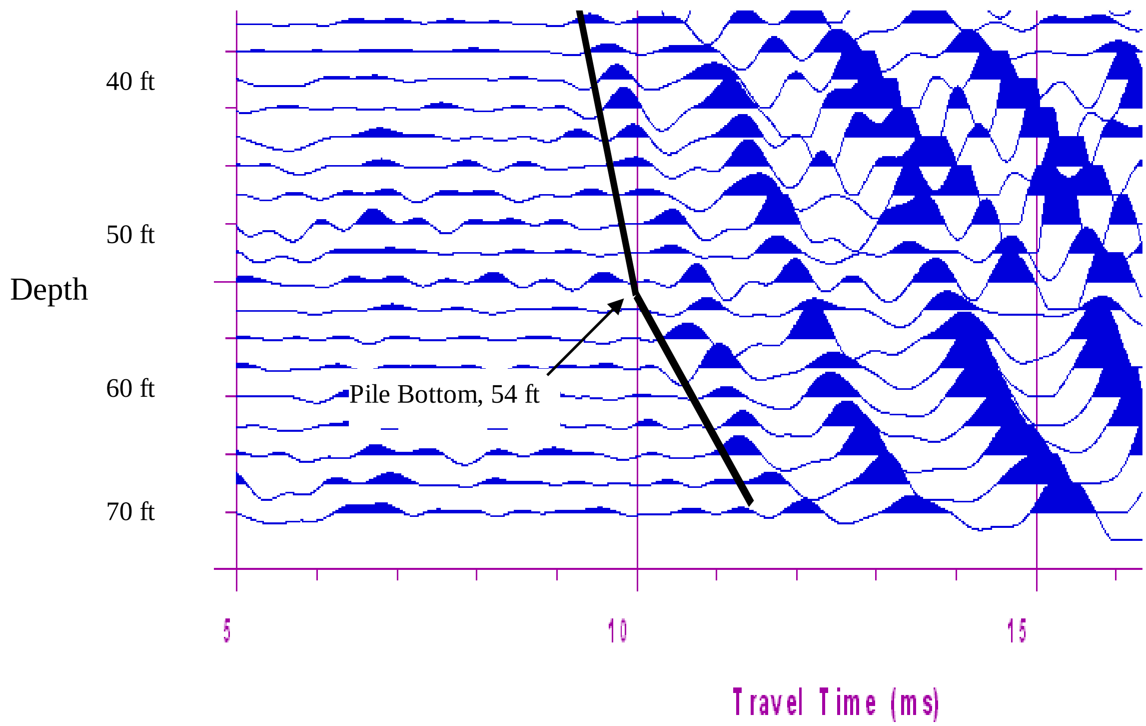

Figure 4- Parallel Seismic Data from Integrated CPT/PS Cone Probe with 3 Pound Plastic Tip Hammer Impact Source
Concrete Pile
I-65 Bridge Site, Mobile, Alabama

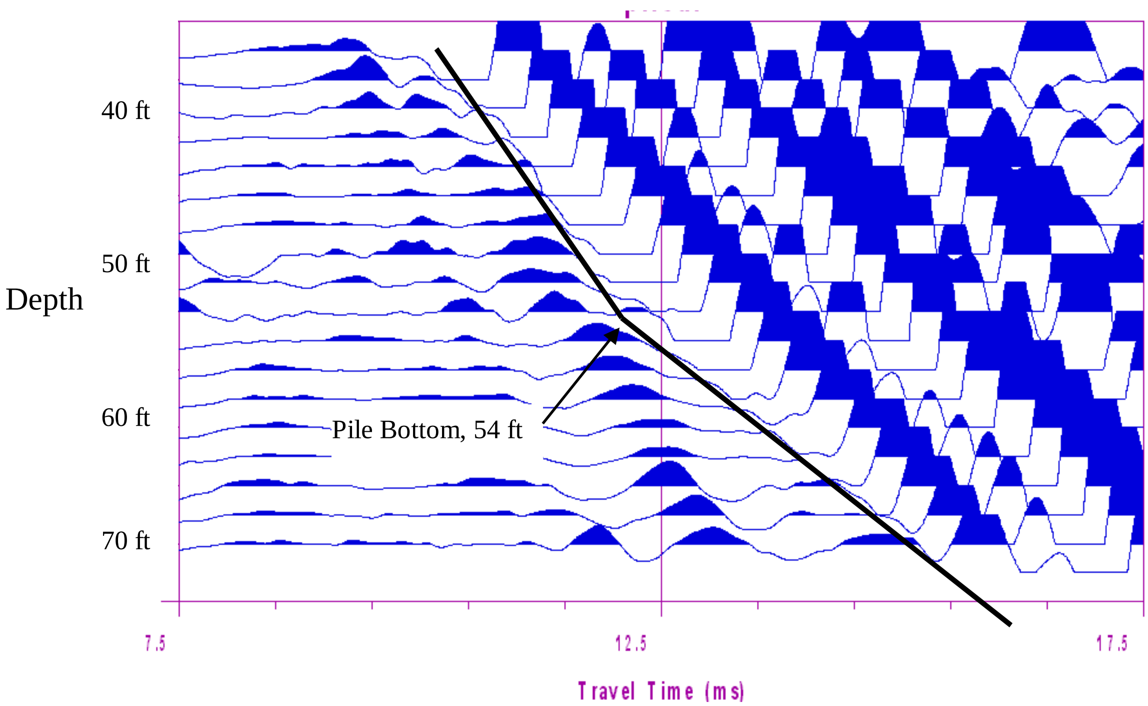

Figure 5- Parallel Seismic Data from a Hydrophone in Water-Filled Cased Borehole with 3 Pound Plastic Tip Hammer Impact Source
Concrete Pile
I-65 Bridge Site, Mobile, Alabama

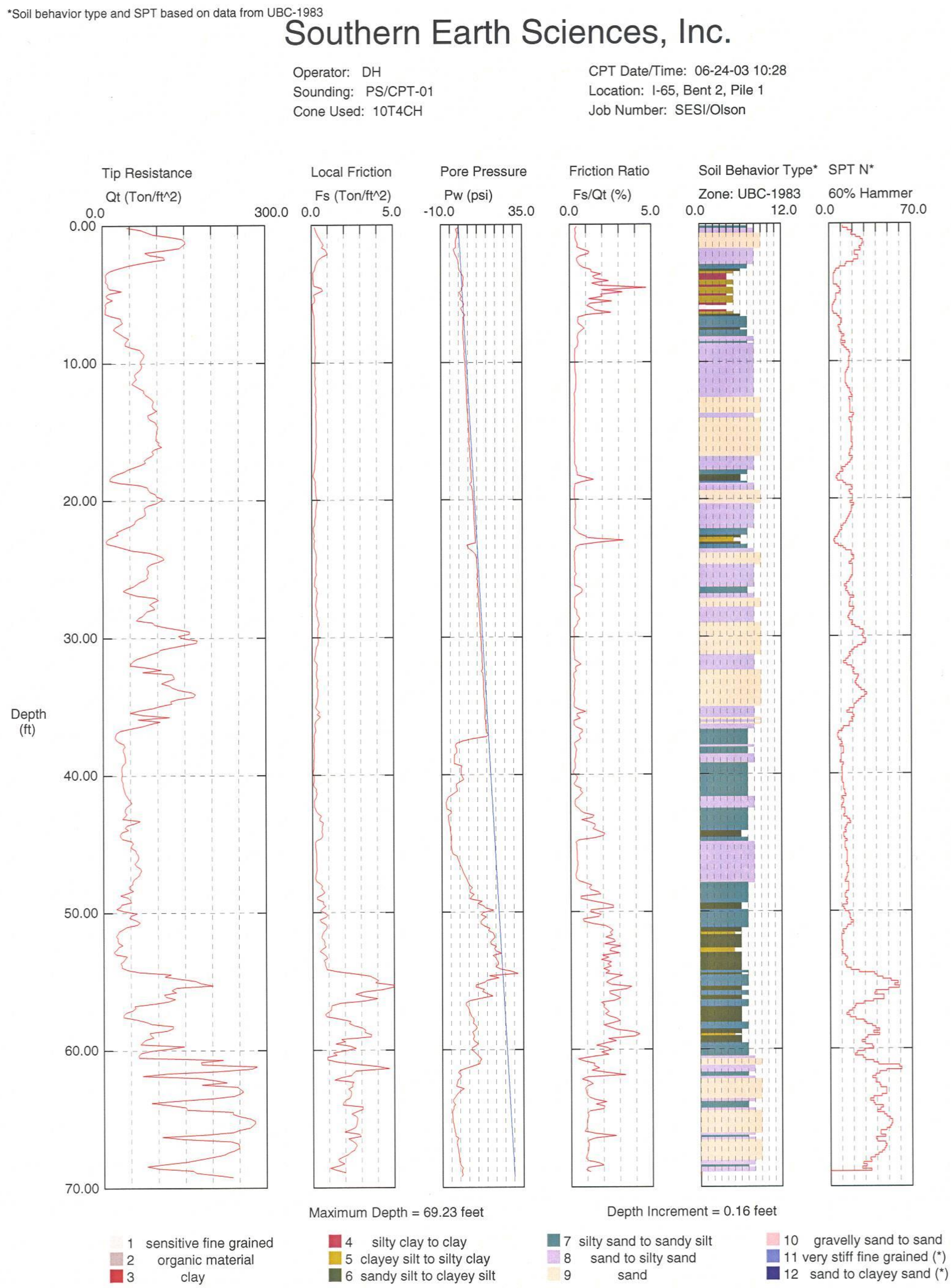

Figure 6- Cone Penetration Test Log
I-65 Bridge Site, Mobile, Alabama