A Rapid Field Soil Characterization System for Construction Control

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ABSTRACT

Soil strength, type, and moisture content are needed to properly assess the load carrying capacity of soil in construction control applications. Currently, no portable, automatic, easy-to-use field methods exist to measure the required soil parameters. In this paper, we describe a new instrument that integrates and extends two proven technologies, the cone penetrometer (CPT) and dynamic cone penetrometer (DCP). The portable Rapid Soil Characterization System (RapSochs) is under development for the US Army to perform near surface assessments to determine trafficability for heavy vehicles and aircraft. In the construction control context, the new device has the potential to eliminate errors in the measurement of soil strength due to soil type and moisture effects. The newly developed technology automates and adds sensing capability to the standard dynamic cone penetrometer (DCP) configuration specified in ASTM D6951. The sensing approach combines cone resistance and sleeve friction sensing from proven piezocone (CPT/CPTu) technology (ASTM D3441) with additional new sensing technologies. A fully automatic prototype system has undergone limited field demonstration at the USACE facility in Vicksburg, MS. Preliminary laboratory and field test results indicate that the required soil geotechnical parameters can be extracted from dynamic penetration data, providing a near surface instrument that can provide accurate soil strength assessment to a depth of one meter.

BACKGROUND

Current State of Practice

Existing pavement design procedures are principally based on either empirical (based on moisture/density relationship) or mechanistic-empirical approaches. Many agencies have recently moved to adopt mechanistic empirical methods for pavement system design. These methods require determination of the resilient modulus to validate pavement system performance against the design. Examples of devices used for construction control are the soil stiffness gauge (SSG), the dynamic cone penetrometer (DCP), the shear vane, the pressuremeter, the dilatometer, the Clegg hammer, and portable falling weight deflectometer. However, two significant issues exist with devices used in the field: they do not measure resilient modulus directly and they do not correct for the influence of soil type and moisture content.

The SSG and related devices, which directly measure stiffness, and the DCP, which provides an index of strength, offer direct monitoring of stiffness and strength of subgrade materials. SSG stiffness and DCP penetrometer index (DCPI), in turn, have been correlated to properties used in design such as resilient modulus (*1*) and California bearing ratio (CBR) (*2*), respectively. Of the devices commonly used in the field, the DCP has the longest history and well established correlations to CBR and resilient modulus (*2,3*). Because measurements of stiffness or soil strength are influenced by soil type and moisture (*4*), special calibration or procedures are generally required. For example, ASTM D6951 provides three calibration equations for use with the DCP on coarse materials, CL, and CH clays.

Cone Penetrometer (CPT) Background

CPT devices operate in a constant-push mode and consist of an instrumented tip that contains sensors to measure cone resistance, sleeve resistance, and in the CPTu configuration, pore pressure. For the CPT configuration, it has been shown in the literature that the ratio of sleeve friction to cone resistance is correlated to soil type (*5*). The undrained shear strength (C_u), as calculated from the cone resistance, can be corrected for soil type and pore pressure (*6*). Addition of CPT sensing functionality plus a moisture sensor would permit soil type and moisture independent measurement of soil strength.

DCP Background

In its standard form, the DCP consists of a rod fitted with a conical tip that is driven into the soil by energy provided by a slide hammer. The hammer is dropped a fixed distance onto an anvil attached to the rod thereby transferring the kinetic energy to a cone shaped tip. If the energy is great enough, the soil fails in shear and the tip advances. The penetration of the rod into the soil as a result of the imparted energy is related to the strength of the soil. As the hammer mass and drop height are known, the kinetic energy is known. For coarse materials, the dynamic cone resistance (q_d) can be related to the test conditions and instrument geometry according to the commonly used Dutch formula (*7*).

$$q_d = (1/A) * \left(\frac{KE}{X}\right) * \left(\frac{M}{M+P}\right)$$

where A is the cross sectional area of the cone, KE is the imparted kinetic energy, X is the incremental penetration (usually referred to as the DCP index (DCPI) and stated in mm/blow), *M* is the mass of the hammer and *P* is the mass of the penetrometer. The penetration *X* is also a function of the angle of the cone. Cone angles of 60° and 90° are typically used.

Many researchers (*2*,*3*) have correlated the DCP index with the established measurement of soil strength (CBR). The general equation is

$$Log(CBR) = K1 - K2(\log(DCPI))$$

where the K1 and K2 are constants that, for the simple penetrometer described, are dependent on soil type and moisture level. CBR can range from >100 for crushed coarse soils to <1 for fine grained materials containing high organic and moisture content. To address the wide dynamic range, a dual mass hammer is utilized. Other devices, such as the Sol Solution PANDA (*8*), use a fixed mass hammer but the impact is controlled manually and measured electronically to better cover the full range of soil strength encountered in the field.

Impedance Spectroscopy Moisture Measurement

Physics of Dielectrics

The electromagnetic response of soil is primarily determined by its dielectric properties. The heterogeneity of soil combined with significant interfacial effects between the highly polar water molecules and the soil solids surface results in a complex electrical response for which good phenomenological theories do not exist. There are three primary polarization mechanisms in soil: bound water polarization, double layer polarization, and the Maxwell-Wagner effect. The bound water polarization results from the fact that water can be electrostatically bound to the soil matrix. The degree of binding varies from unbound or free water at a great distance (> 10 molecular diameters) from the matrix surface to heavily bound, or adsorbed, water. Double layer polarization is due to separation of cations and anions in an electric double layer around clay particles. It is a surface phenomenon that is dominant at frequencies below 100 kHz (*9*). Double layer polarization is mostly observed in soils containing a large fraction of clay. The Maxwell-Wagner effect is the most important phenomenon that affects the low radio frequency dielectric spectrum of soils. The Maxwell-Wagner effect is a macroscopic phenomenon that depends on the differences in dielectric properties of the soil constituents resulting from the distribution of conducting and non-conducting areas in the soil matrix.

Impedance Spectroscopy

The author's research has shown that typical soils suitable for engineering use exhibit a Maxwell-Wagner relaxation in the 0.2-30 MHz range (*10*). Above this frequency range the dielectric response is empirically described by mixing equations in which the matrix bulk dielectric constant is proportional to the sum of the products of the volume fractions and dielectric constants of the constituents (*11-13*). During soil compaction, the volume fraction of air is reduced and the volume fractions of soil and water are increased. This results in an increase in both the permittivity and conductivity of the soil.

A qualitative representation of the dielectric properties of moist soil is presented in Figure 1. Research by the authors has identified features in the Maxwell-Wagner portion of the spectrum that are used in a parametric inversion method to measure wet density and volumetric moisture. Then, the dry density and gravimetric moisture content of compacted soil are calculated using standard methods (ASTM D6938 for example).

The EIS soil density/moisture device is initially calibrated in the laboratory using a typical well-graded GP-GM soil used in construction. Then, gradations that span the range of well graded as defined by the coefficient of curvature and coefficient of uniformity, were to used to develop adjustments to cover the range of field conditions and stone origin (run-of-bank or crushed). Large (6 ft x 6 ft x 1 ft deep) samples prepared at moisture levels determined by the Proctor Test ASTM D698 to be appropriate for typical construction uses of the material are compacted to densities in the range from 90-100% of the optimum dry density. Reference total density readings are taken using ASTM D6938 and reference moisture readings using ASTM D2216. Features containing moisture and density information are extracted from the impedance and converted to wet density and volumetric moisture using regression analysis. Job specific parameters related to the soil type and gradation are used to adjust the laboratory calibration to the soil under test. Currently, three reference calibrations are stored in the device; one for coarse well-graded materials with non-plastic fines, a second for open graded coarse materials, and a third for materials with a large clay fraction. Figure 2 shows a typical result for moisture and density determination using EIS technology. The data shown was taken during validation testing of the algorithms on typical construction soils covering the useful range of density, gradation, and moisture content.

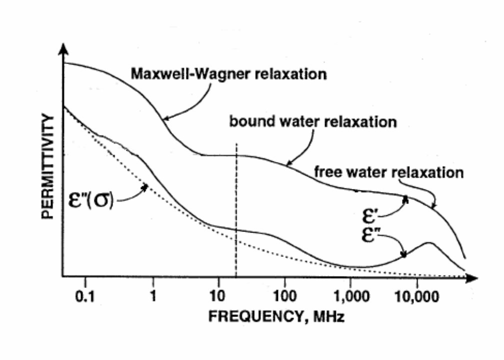

Figure 1. Dielectric Spectrum of Soil (adapted from Hilhorst 1998)

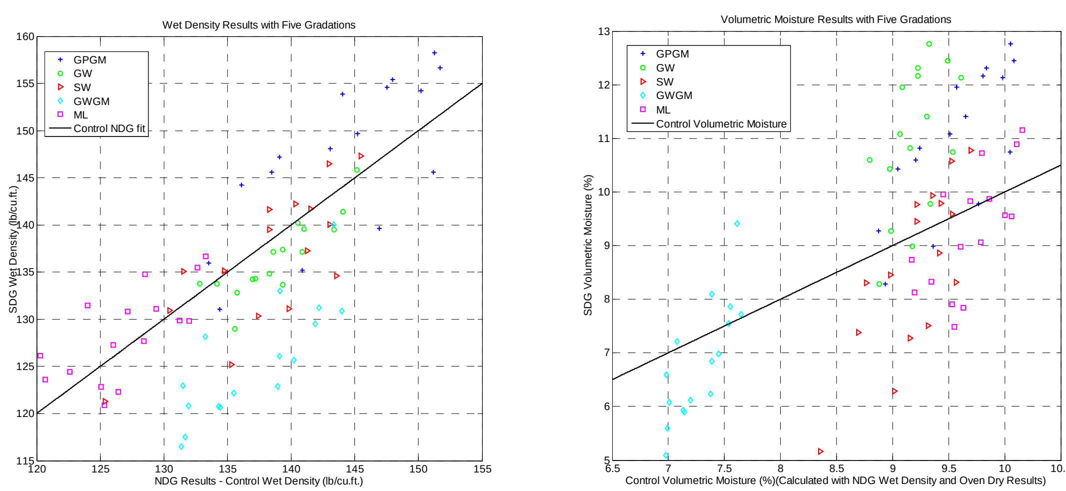

Figure 2 Soil Density Gauge Validation Test Results.

Research Approach

Some of the known issues with the standard DCP include: dependency of CBR correlations on soil type, inability to measure near the surface in cohesionless materials, errors due to adhesion at depths greater than ~12 in. (30 cm) in highly plastic materials, and sensitivity of the results to moisture level (*3,4*). This paper describes a new device that is developed to address these issues. The paper describes the development of a new fully automatic portable capability that integrates the measurement of soil strength, soil type, and moisture content into a single field instrument that has the potential to better address construction control using stiffness type measurements by improving the accuracy of the widely used DCP. The device is called Rapid Soil Characterization System (or RapSochs). The general approach is to incorporate the established sensing capabilities used in electronic cone penetrometers (CPT) into an automatic DCP-like instrument.

The funding for the current research was provided by the US Army Engineer Research & Development Center to develop a system for characterizing the in-situ soil properties that determine trafficability, namely soil strength (CBR), soil type, and gravimetric moisture content. These measurements would be used for the following applications: (1) selection of optimal locations for vehicle crossings on soil surfaced terrain, (2) prediction of soil deformation under vehicular traffic, and (3) site selection for contingency infrastructure facilities, such as runways.

SYSTEM DESCRIPTION

Successful development of the new capabilities required solutions to several challenging problems: extraction of CPT equivalent information from dynamic sensor data, high performance, low weight and power consumption, miniaturization of sensors and critical signal conditioning functions to fit into a DCP size penetrometer and, reliable operation of the sensors in a high shock environment.


Figure 3. Prototype Rapsochs

The portable soil characterization system is configured as a miniature pile driver that employs a battery powered adaptive control system to raise and drop a 20 lb (9.1 kg) hammer. The hammer mass, the drop height range, cone angle and cross section area are based upon the established ASTM D6951 DCP. The prototype system is shown in Figure 3. In ASTM D6951, the full range of soil strengths is addressed using two masses. In the RapSochs, a single mass is combined with adaptive control of drop height based upon previous penetrations. The maximum penetration depth for the prototype is 36 in (0.9 m). The instrumented penetrometer contains sensors that measure tip strain (cone resistance) and sleeve strain in a CPT style subtraction cone configuration. An accelerometer is mounted behind the tip to measure axial acceleration. The accelerometer is also used to sense the hammer impact and trigger the data acquisition sequence. Eventually, numerical integration of axial acceleration will produce velocity (useful to evaluate strain rate effects) and displacement. Currently a string potentiometer measures the total penetration and penetration per blow (DCPI). An electrical impedance spectroscopy (EIS) sensor measures the soil moisture. The addition of a moisture sensor provides necessary information to assess soil (clays) workability and/or plasticity at the time of testing, to correct the strength measurements for the influence of moisture, and assess the result of seasonal changes in moisture content.

A miniaturized electronics module provides signal conditioning and analog-to-digital conversion for the penetrometer sensors plus provides the measurement circuit for the moisture sensor. Data is acquired at 10 kHz. for 0.2 seconds to capture the response to the hammer impact. Pre-trigger sensor data is used to dynamically zero each sensor prior to the impact to remove the effects of drift and hysteresis. Figure 4 shows the raw penetration, acceleration, tip and sleeve force data for a single impact in a sandy CH clay.

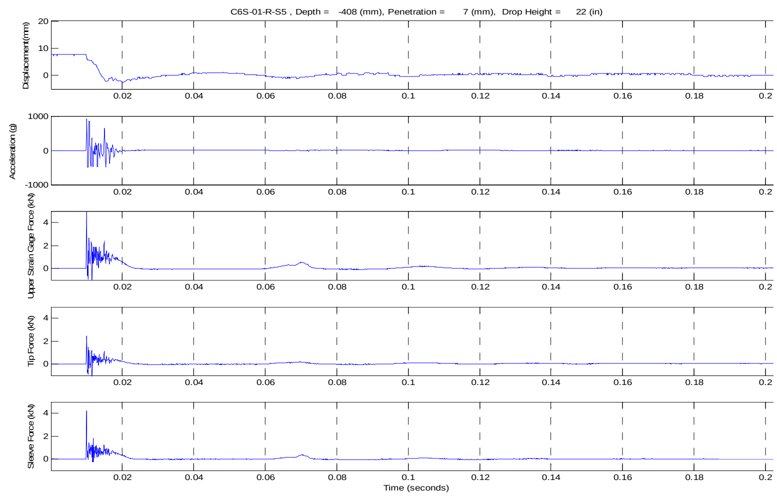

Figure 4 Typical Raw Data – Sandy Fat Clay.

LABORATORY TESTING

Test Objectives

The scope of the laboratory test plan was to assess the ability of the RapSochs to determine the soil strength, moisture content, and soil type. A second objective was to assess the functional operation and reliability of the RapSochs prototype. During this testing, the hammer was dropped manually as the automation aspect of the system was still under development. The main purpose of tests was to validate the CBR measuring capability of the RapSochs by comparison with the performance of a standard dual mass DCP (ASTM D6951) in laboratory prepared materials. The DCP was used as the benchmark for soil strength profiles as considerable Army experience exists using this device. Tests were designed to validate the functional and performance features of the RapSochs in a controlled environment. Tests were conducted in the SoilBED facility at Northeastern University.

USCS	D_{50} (mm)	(C_u)	(C_c)	# of Tests		CBR++	
				RS+	DCP	Min	Max
SP (Poorly graded sand)	0.3	2.7	1.0	5	4	0.5	1.6
SP (Poorly graded sand)	0.3	2.7	1.0	0	0	0	0
CH (Sandy Fat Clay)*	<0.075			2	2	4	23
SC (Clayey Sand)**	0.42			1	1	2.3	2.7
SC (Clayey Sand)**	0.42			1	0	-	-
SW (Well graded sand with gravel)	4.65	18	1.8	3	2	2.4	35
SP (Poorly graded sand)	0.59	2.9	1.0	5	4	1	4.7
SP (Poorly graded sand)	0.59	2.9	1.0	5	4	1	5
SP (Poorly graded sand)	0.59	2.9	1.0	5	4	-	-
ML (Sandy silt)	<0.075			4	4	20	50
ML (Sandy silt)	<0.075			4	4	9	20
SW (Well graded sand with gravel)***	4.65	18	1.8	7	-	-	-

* Plastic Limit =47 %, LL = 425%
** Plastic Limit =28 %, LL = 403%
***Includes Sample MS0, MS1, MS2, MS3, MS4, MS5 and MS6.
+ RapSochs Tests
++ CBR is estimated using correlation based on DCP index.

Figure 5 Laboratory Test Matrix.

Soil Samples

A total of 18 samples were prepared using five different soil types that covered the main diagonal of the Robertson soil type curve. The individual samples varied in soil density or moisture. Standard laboratory tests were used to determine the geotechnical properties of the soils tested and determine the optimum density and moisture level for sample preparation. The samples were prepared in cube shaped containers measuring 24 in (61 cm) on a side. Tested soil strength spanned the range from loose to CBR 50. Moisture content varied from very dry to saturated. The matrix of tests is shown in Figure 5. For each soil type, at least one sample was prepared at optimum moisture as defined by ASTM D698. Samples were prepared by placing moisturized soil into the testing container and compacting in 2 in (50 cm) layers using the standard Proctor hammer and compaction energy. Up to nine penetrations (five RapSochs and four DCP) were conducted in each sample. Penetrations were separated by 7.5 tip diameters (14 cm) from each other and from the container walls. The total depth of penetration was approximately 20 in (500 mm). DCP penetrations were made using the standard drop height of 22.6 in (575 mm). RapSochs penetrations were made with variable drop height to emulate the automatic operation that would attempt to maintain penetration per blow of no greater than 12.5-25 mm.

Effect of Variable Hammer Drop

As a consequence of variable drop height of the RapSochs, the strain rate in the soil will also vary. An objective of this experiment was to determine the influence of strain rate on achieved penetration in a range of materials. The effect of variable hammer drop height was studied by applying different drop heights and observing the resultant penetration per blow in a region of the sample where the penetration per blow was nominally constant. After several blows of the maximum drop height of 22 in. (559 mm), the drop height was decreased to 10 in. (254 mm) and 15 in. (381 mm), and then back to 22 in. (559 mm) for the remainder of the test. The penetration per blow corrected for drop height is presented along with drop height in Figure 6 for different soil samples.

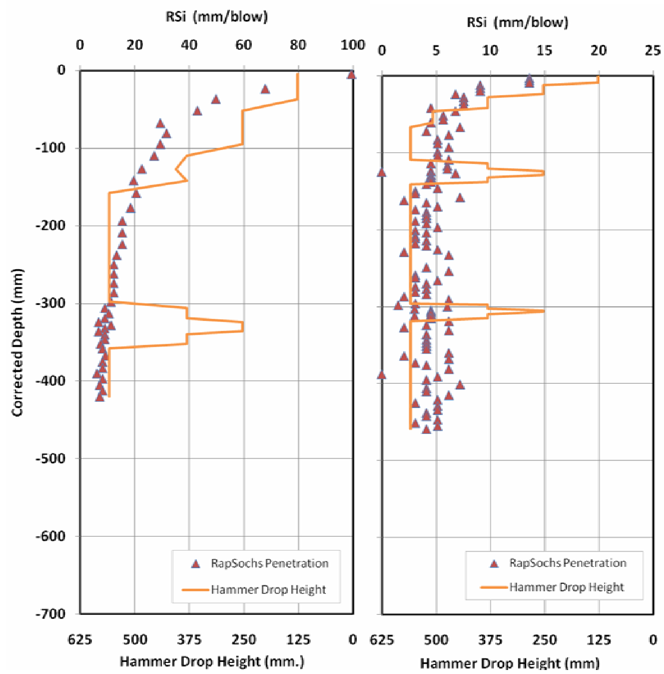

Figure 6 RapSochs penetration per blow versus RapSochs total penetration for CH on left and ML (CBR 50) on right.

In this graph the penetration per blow is normalized to the DCP standard of 22.6 in. (575 mm). The region of variable drop height is bracketed by regions of constant 22 in. (559 mm) drop height. Comparison of corrected penetration data around the drop height change shows no observable trend or shift in data. However, a closer look shows that data is more scattered when the applied energy is lower. This can be explained by the non-homogeneous nature of soil and its scale effects.

Soil Behavior Classification

Soil type measurements using the sleeve and cone resistance are widely used in interpretation of CPT. With CPT devices, the sleeve and cone signals are constant for fixed rate pushing through homogeneous material. Complicating the extraction of the soil type information from the dynamic data is the presence in the signals of high frequency information due to the compression wave propagation and its interaction with hammer, impedance discontinuities in the penetrometer, and the soil. To extract the similar features from the RapSochs data the tip force and sleeve (total - tip) force signals are filtered and the maximum peak of the pulse is extracted. The tip force is then normalized for the mass of the hammer and drop height and plotted versus friction ratio (sleeve/tip expressed as a percentage). One data set for each soil sample was used for the soil classification analysis. Results are shown in Figure 7. Distinctive classification of soil behavior is clearly observed in this graph.

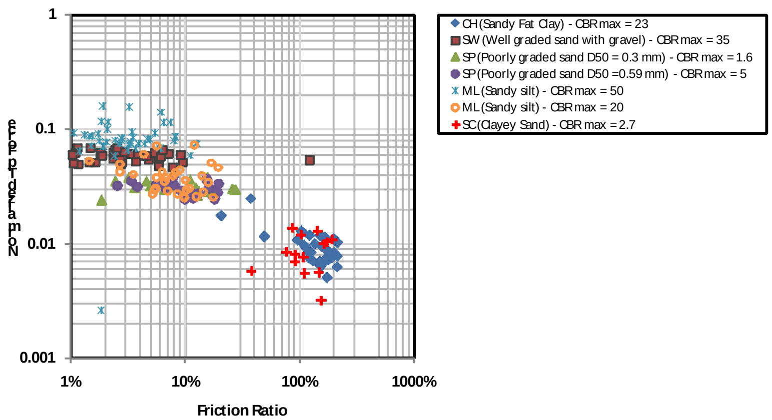

Figure 7 RapSochs Data for soil behavior type classification.

PRELIMINARY FIELD TEST RESULTS

The first field testing of fully automatic prototype was conducted at the Army's Waterways Experiment Station in Vicksburg, MS. Side by side testing was conducted using a DCP as the standard for soil strength. Full depth penetrations were conducted in three on-site locations; buckshot clay (CH), a well compacted silt, and a layered deposit of 0.5 m sand over clay. One of the goals of the adaptive hammer drop system is to achieve an average penetration per blow no greater than 12-25 mm. There are several geometry and other factors that could influence the response compared to a standard DCP. There are several implicit assumptions in Cassan's formula that have been questioned in the literature. Cassan's formula suggests only the kinetic energy, cone area, and penetrometer mass distribution influence the penetration. Tsai et. al., (*14*) have shown that the ratio of the hammer area to the anvil area and the specific hammer shape influence the energy transfer. In CPT, much has been written on rate effects and in some cases additional understanding about soil behavior is obtained by deviating from the standard rate of penetration (*15*). The authors have derived analytical results that predict that the cone angle influences the penetration. In order to implement the friction sleeve and moisture sensor, the Rapsochs penetrometer diameter is the same as the tip, not smaller as in the DCP. Finally, an elastomer is installed on top of the anvil to reduce peak impact acceleration and the acoustic signature. However, as shown in the previously described testing, no significant strain rate effects have been observed in RapSochs data for the coarse materials tested to date.

In order to assess the influence of the explicit factors in Cassan's equation, the raw RapSochs penetration data is converted to an equivalent DCP penetration by the following relation:

$$X_D = X_R(M_R + P_R)M_D^2 h_D \big/ (M_D + P_D)M_R^2 h_R = 16.45 X_R / h_R$$

where the R subscripts apply to the RapSochs terms, the D subscripts the DCP terms in Cassan's equation, and the h's are the drop heights in inches. Figure 8 shows the DCP and RapSochs results (converted as described) expressed in CBR using the ASTM D6951 conversion equation for the SP over CH layered test location. In the Rapsochs data, all points are shown. In the DCP data, as many as three drops were taken to produce a single point. The DCP hammer mass was changed at 515 mm from 17.6 lb (8 kg) to 10.1 lb (4.6 kg). The drop height of the Rapsochs was automatically controlled to produce penetrations of 25 mm or less.

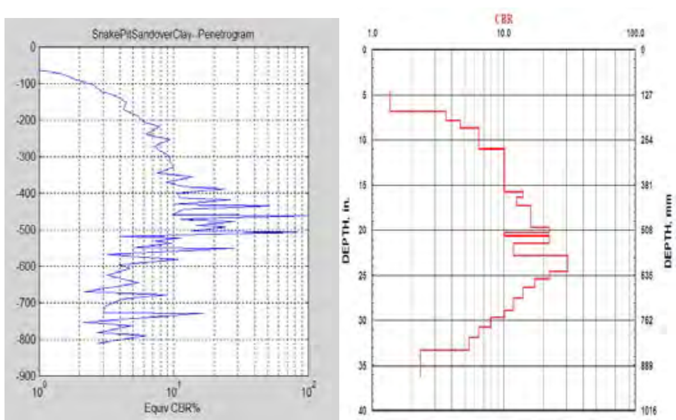

Figure 8 Side by Side DCP and RapSochs – SP over CH.

Figure 9 shows the improved spatial resolution of the RapSochs compared to the DCP in a low strength material. The DCP record was taken using the 17.6 lb (8 kg) hammer.

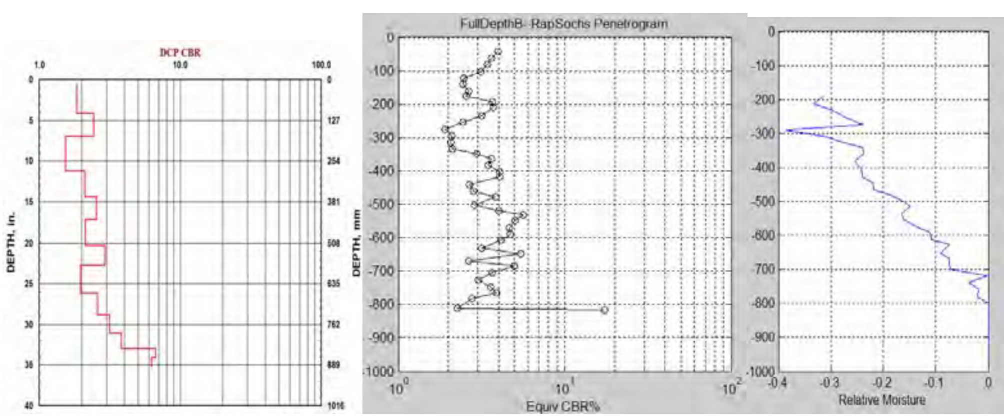

Figure 9 DCP and RapSochs Resolution Comparison.

CONCLUSIONS

1. The program results to date have established that a portable, automatic DCP type device for accurate soil characterization for construction control is feasible.

2. The penetrometer resident sensors and electronics are able to withstand the shock and vibration induced by the hammer impacts in the hardest materials.

3. The adaptive control drop height produces increased and uniform spatial resolution through the measuring range and does not appear to degrade the correlation with the DCP for coarse materials due to the variable strain rate. Additional data must be taken in fine materials to determine if the variable strain rate affects the penetration. This capability may also result in improved capability to localize layer transitions.

4. Data equivalent to CPT sleeve and tip strain data can be obtained from the dynamic data with appropriate signal processing to facilitate assessment of soil type.

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