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Characterization of Intermediate and Structured Soils with a CPT-Interface Response Soil Classification Framework

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Abstract. This paper describes a soil classification framework for Cone Penetration Test (CPT) data that uses a multi-sleeve attachment with friction sleeves of varying surface roughness for measurement of the soil interface shear response. The characterization exercise presented herein focuses on intermediate and structured soils, and provides comparison with the characterization results provided by other existing classification systems. The results indicate that the soil classification provided by the proposed framework better agrees with index properties as compared to other systems. The proposed framework is based on two independent parameters that capture different aspects of soil behavior: the normalized Multi Friction Parameter (MFP), and the normalized tip resistance (Q_{tn}). The MFP is obtained using multiple rough and conventional CPT friction sleeve measurements in the same sounding that allows for capture of the interface strength versus surface roughness relationship while Q_{tn} captures the soil's internal strength and state through measurement of bearing capacity resistance. A discussion of the practical implications of utilizing the proposed soil classification system is provided.

Keywords. Soil-structure interaction, interface shearing, laboratory testing, clay.

1. Introduction

One of the primary objectives of site characterization activities is to capture soil profiles with depth where the materials can be classified and grouped into their characteristic layers. Soil classification is often the necessary beginning to any geotechnical design as it provides information for a first-level assessment of potential geotechnical challenges and opportunities at a given site. For instance, soft clays could result in large foundation settlements, loose sands could present liquefaction hazards, and dense/compact soils in the near surface could provide for foundation savings. Consequently, numerous soil classification systems have been developed over the years to help geotechnical engineers accurately classify soils and to identify such potential challenges and opportunities.

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Commonly used soil classification systems that use Cone Penetration Test (CPT) results include those by [1-3]. These systems use data such as the measured and normalized tip resistances, q_t and Q_{tn}; the measured friction sleeve, f_s; the friction ratio, F_R; and the measured and normalized excess pore pressures (u_2, U_2, and B_q).

The widespread use of CPT soil classification systems is due to their relative ease for automated implementation, their relatively high reliability for classification, and the growing dependence of industry on the CPT. However, it is well-documented that CPT-based soil classification systems often provide inaccurate soil type classification results of cemented, residuum, and intermediate soils [2,4,5]. These "mis-characterizations" mainly result for classifications based on soil behavior type (SBT) which reflects the response of the soil to the mechanical loading imposed during CPT penetration (e.g. bearing capacity in q_t, friction against a smooth surface in f_s). However, SBTs do not necessarily reflect inherent soil characteristics such as gradation and structure. This paper presents a soil classification framework that uses the relationship of interface shear strength between a soil and a solid surface and the roughness of that solid surface [6]. This relationship has been shown to directly reflect soil properties by various researchers [7,8]. The use of this new framework does not discard use of conventional CPT SBT, but rather offers the opportunity to combine systems for a better site characterization.

2. Multi-sleeve modules for CPT and field sites

2.1. First and second generation modules

The soil classification system presented herein uses the multi-sleeve modules for CPT probes developed at the Georgia Institute of Technology. These modules overcome some of the shortcomings of the conventional CPT, such as the position of the friction sleeve within the highly stressed zone behind the tip and the prescribed friction sleeve smooth surface [9-12].

Both existing generations of multi-sleeve modules can be attached to the back of a 15 cm^2 CPT probe, and consist of four individual friction sleeve sensors that can be equipped with friction sleeves with varying surface roughness, as shown in Figures 1a and 1b. The first generation module, called the Multi-Friction Attachment (MFA), is typically equipped with friction sleeves that increase sequentially in roughness from the CPT tip. Within one sounding, the MFA provides the conventional q_t, f_s, and u_2 readings as well as four additional friction sleeve readings that can be used to construct the in-situ interface strength-surface roughness relationship [9,11]. The second generation module, the Multi-Piezo-Friction Attachment (MPFA), is equipped with five additional pore pressure transducers along the shaft of the device to provide excess pore pressure readings as a result of soil shearing against surfaces of different roughness [12,13]. [6] provides an overview of the results obtained from the MFA and MPFA in different soils. [9] evaluated the potential effects of wear of the friction sleeves on MFA measurements and concluded the effects to be negligible over dozen of tests on various soil types. The effect of temperature on the measurements has however not been assessed to date.

2.2. Textured sleeves for multi-sleeve modules

The friction sleeves equipped on the MFA and MPFA have a surface texturing pattern that allows the magnitude of their surface roughness to be controlled while ensuring that the surface does not clog with soil particles during a sounding. The friction sleeves have the staggered diamond texture pattern shown in Figures 1c and 1d. The surface roughness of the friction sleeves is controlled through variations of the diamond element height, H, from values between 0.01 mm to 2.00 mm, which is equivalent to the R_{max} surface roughness parameter. All other texture parameters, such as the element length (D), width (W), spacing (S), and angle (β) are kept fixed [9,10].

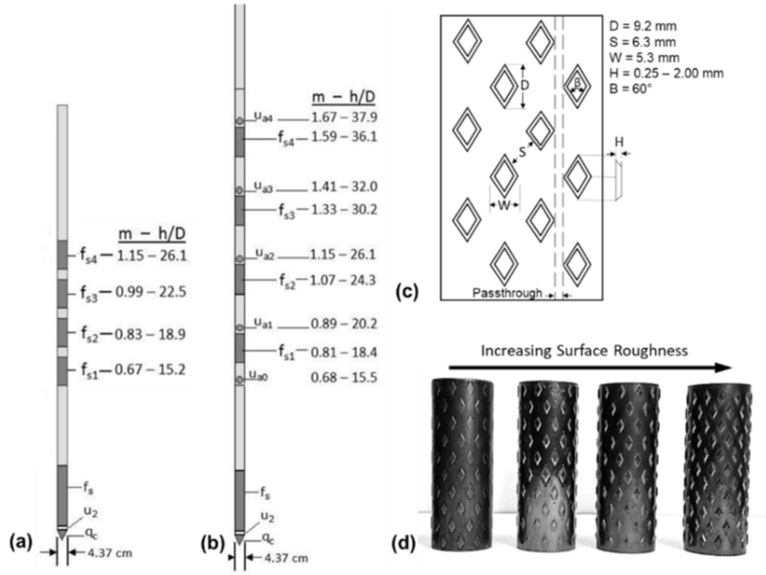

Figure 1. Multi-sleeve modules for CPT: (a) MFA and (b) MPFA with distance from CPT tip. (c) Diagram and (d) photograph of textured sleeves.

2.3. Testing sites

Field tests have been performed with the MFA and MPFA at over 15 sites in the USA and Australia. These sites contain a wide range of geologic strata, from soft and stiff clays, to cemented sands and sandy silts, to loose and dense quartz sands, as described in [6]. Evaluation of the capability of the soil classification framework described in the following section to discern intermediate and cemented soils is based on soundings performed at five sites. Table 1 provides mean particle size (D_{50}), percentage of fines, and liquid limits obtained for samples from those sites. The control sand strata, consisting of uncemented quartz sand deposits, are the SRVT and LS sand layers. The LPWA layer consists of a cemented calcareous sand. The intermediate soils consist of the Opelika crust, sand/silt, and silt/clay which are part of the Piedmont residuum. The cemented fine-grained soil is the MPSC which is a highly overconsolidated sandy clay to sandy silt. Additional soil data for these sites can be found in [6].

3. Proposed CPT-interface response soil classification framework

The proposed CPT interface response soil classification framework adds the relationship between the shear strength mobilized at a soil-solid interface to the use of Q_{tn} for soil characterization. This interface response relationship depends on several factors, such as the soil type, range of particle sizes, particle angularity, and soil density, as well the surface roughness and hardness of the solid surface and the loading rate [14,15]. The relationship can be described with a bi-linear function, where the interface strength increases linearly as the surface roughness is increased up to a "critical roughness" value. Subsequent increases in roughness produce no change in the interface strength [7,8].

Table 1. Geologic strata used for classification of intermediate and cemented soils.

Geologic Strata	Location	Description	D_{50} (mm)	% Fines	Liquid Limit (%)
SRVT Sand	Vermont, USA	Uniform fine quartz sand of loose to medium density	0.23	3	N/A
LS Sand	South Carolina, USA	Medium dense quartz sand underlain by loose sand	0.19	1	N/A
LPWA - Ledge Point Calcareous Sand	Western Australia	Coastal cemented calcareous sand	0.21	4	N/A
MPSC - Cooper Marl	South Carolina, USA	Stiff structured/cemented sandy clay to sandy silt, high OCR	0.003 - 0.04	62 - 96	37 - 110
Opelika - Piedmont Crust	Alabama, USA	Residuum crust, very high OCR	0.03	62	N/A
Opelika - Piedmont Sand/Silt	Alabama, USA	Residuum silty sand to sandy silt	0.21	30	41
Opelika - Piedmont Silt/Clay	Alabama, USA	Residuum silty clay to clayey silt	0.05	50 -65	42

3.1. Normalized sleeve stress parameter and classification index

The rate of increase in interface strength with increasing surface roughness is dependent on soil gradation because a given asperity has a greater height relative to a smaller particle than to a larger particle. In addition, the increase in strength with increasing roughness is greater for gravels, then for sands, silts, and clays, respectively [6]. This trend is captured with the Multi-Friction Parameter (MFP), defined as:

$$MFP = \frac{2.5\,\sigma'_{v0}}{\tau_{0.50}-\tau_{0.00}} \tag{1}$$

where σ'_{v0} is the initial vertical effective stress, $\tau_{0.50}$ is the isolated sleeve friction for a textured sleeve with a diamond height of 0.50 mm, and $\tau_{0.00}$ is the sleeve friction for a smooth, conventional CPT sleeve [6]. Coarser soils exhibit a greater increase in stress from $\tau_{0.00}$ to $\tau_{0.50}$; thus the value for MFP becomes smaller as the soil becomes coarser as shown in Figure 2. The MFP parameter can be used with the normalized tip resistance Q_{tn} to develop a multi-friction soil behavior index, I_{MF}:

$$I_{MF} = \{[7.3 - \log(Q_{tn})]^2 + [0.5 + \log(MFP)]^2\}^{0.5} \tag{2}$$

3.2. Soil classification

Contours of I_{MF} values can be plotted in log Q_{tn}-MFP space to develop concentric circles in a similar manner as the [1] soil classification systems. The resulting chart is shown in Figure 3a. The proposed chart successfully classifies a wide range of soils, as shown in Figure 3b, including clean quartz and calcareous cemented sands, sandy, silty and clayey mixtures, silts, soft and over-consolidated clays, and cemented sandy clays. The Q_{tn}-MFP classification is in agreement with index properties (i.e. grain size distributions and Atterberg limits), as described in [6]. In general terms, the data moves up and to the left as the internal friction angle and particle size increase.

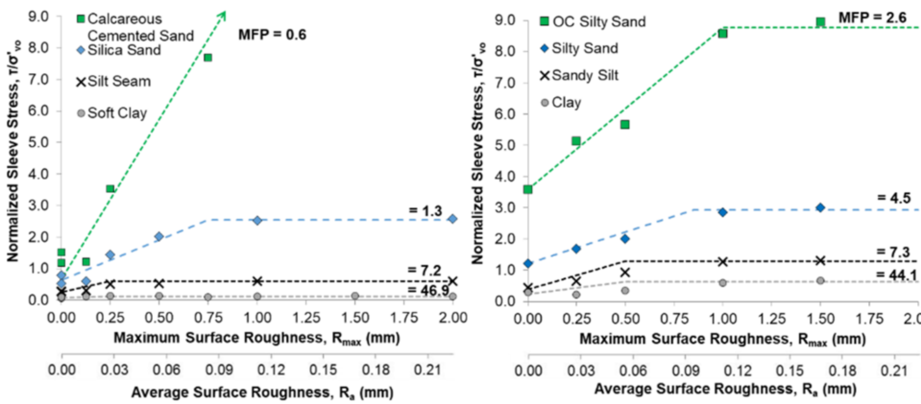

Figure 2. Normalized sleeve stress versus surface roughness from soundings in different geologic strata.

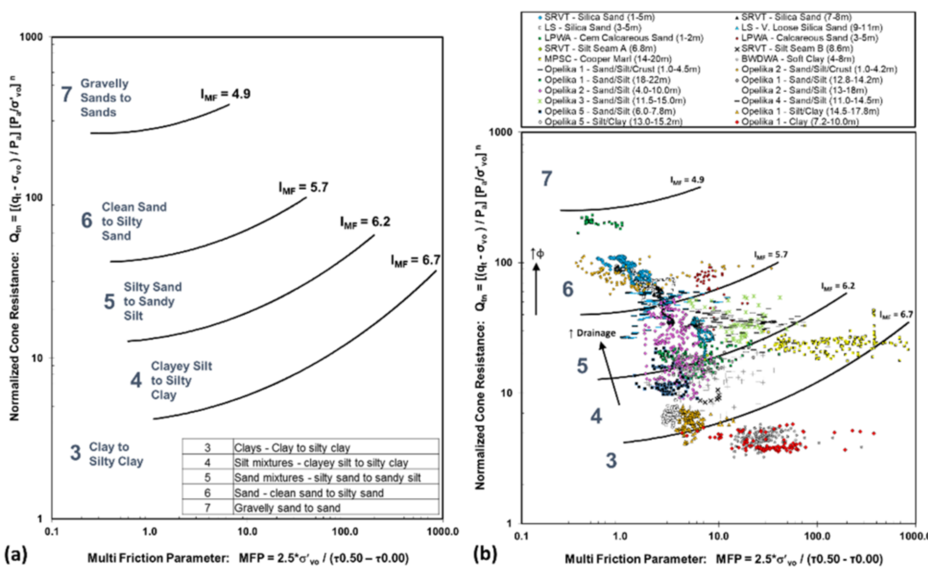

Figure 3. (a) Proposed soil classification chart, and (b) classification of various soils.

3.3. Classification of intermediate (silt and silt mixture) soils

The proposed CPT-interface response soil classification system successfully classifies sandy silts and silty sands, as shown in Figures 4a and 4b in zones I and VI. Field samples of these soils obtained from adjacent boreholes indicated a D_{50} of 0.21 mm, a fines fraction of 31%, and a liquid limit of 40% (Table 1). Silty clay soils are also correctly classified, as indicated in zone V, with a D_{50} of 0.05 mm, fines fraction between 50 and 65%, and liquid limit of 42%. Finally, the overconsolidated clays located in a desiccated crust are incorrectly classified as sands and sand mixtures (zone II) even though they have a D_{50} of 0.03 mm and a fines fraction of 62%.

Data from the same soundings indicate that the [6] chart provides a different classification, as shown in Figures 5a and 5b. The silty mixture soils in zone I are incorrectly classified as clays, in agreement with results reported by [4]. In addition, the sandy silt soils in zone VI are incorrectly classified as silt/clay mixtures. On the other hand, the overconsolidated crust soils in zone II are correctly classified as stiff fine-grained in the Q_{tn}-F_R chart. This comparison suggests that the proposed interface response system better classifies intermediate soils prone to partial drainage during CPT soundings, possibly due to the strong influence of gradation on the interface response. However, the Robertson system better classifies overconsolidated clayey soils.

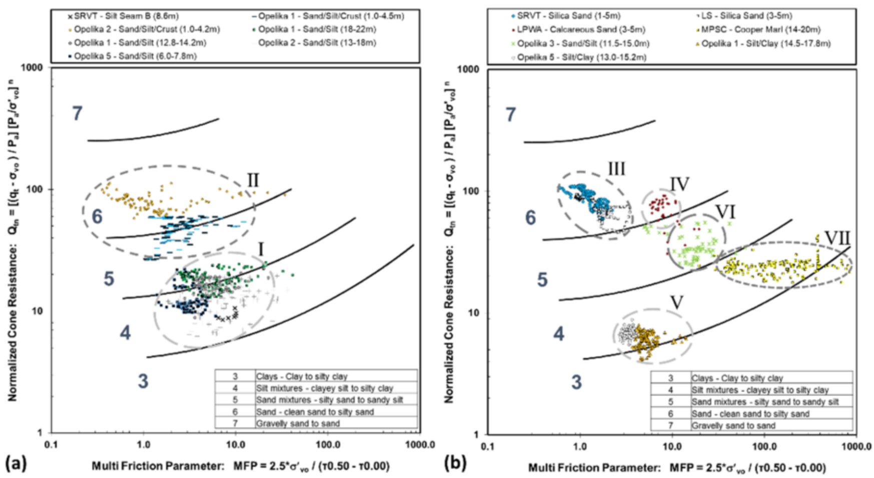

Figure 4. Proposed soil classification chart with data from: (a) intermediate soils, and (b) silica sands, cemented sand, intermediate soils, and cemented sandy silt.

3.4. Classification of structured soils

The interface MFP parameter is shown to differentiate structured soils as they plot to the right in the Q_{tn}-MFP chart relative to their unstructured counterparts, as shown in Figures 4a and 4b. The cemented calcareous sand (LPWA) in zone IV plots to the right of the uncemented quartz sands in zone III (SRVT and LS). In a similar manner, the stiff cemented/structured sandy clay to sandy silt, known locally as the Cooper Marl, (MPSC in zone VII) plots to the right of the silty and clayey mixtures shown in zones I, V, and VI. It is likely that this trend is due to breakage of cementation bonds by the cone tip during penetration. This may result in the friction sleeves measuring response against a disturbed/destructured soil, reflected as an increase in MFP parameter response.

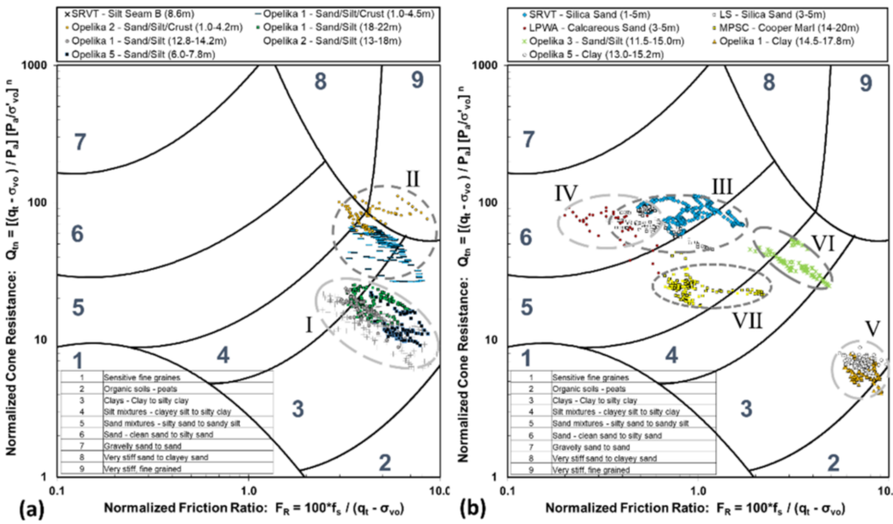

Figure 5. Robertson (1990) soil classification chart with data from: (a) intermediate soils, and (b) silica sands, cemented sand, intermediate soils, and cemented sandy silt.

The Robertson system also appears to differentiate structured from unstructured soils. However, in this system the data plots to the left in Q_{tn}-F_R space, as shown in Figures 5a and 5b in zone IV relative to III, and zone VII relative to I, V, and VI. The stiff cemented sandy clay to sandy silt in zone VII is misclassified as a sand mixture in this system, despite field samples indicating a D_{50} between 0.003 and 0.04 mm, fines fraction between 62 and 96%, and liquid limits between 37 and 110% [16]. Misclassification of these soils has been reported by other authors such as [7], who highlight the propensity of this system to mis-classify cemented/structured soils. [17] provides an update to this system with an additional chart that uses shear wave velocity to successfully identify structured soils.

4. Conclusions and practical implications

This paper presents a new soil classification framework that uses at least two friction sleeve measurements obtained with an attachment for CPT probes. The proposed parameter, MFP, is based on the increase in interface strength with increasing surface roughness of the friction sleeves (Eq. 1). The reported trends show that MFP increases as the soil transitions from coarse-grained to fine-grained. The Q_{tn}-MFP soil classification chart successfully differentiates between sand, silt, and clay mixtures, as well as between structured sands and clay mixtures relative to their unstructured counterparts.

The comparison in classification between the proposed framework and the Robertson system highlights the fact that each system proves more adept at classifying certain soil types. For instance, the proposed system better classified the tested sandy, silty, and clayey mixtures and cemented soils, while the Robertson system better classified stiff overconsolidated fine grained soils. As the MFA and MPFA attachments can be mounted behind a conventional CPT probe, the data from a single sounding can be used to classify soils using both systems, in addition to others such as the Ramsey and Schneider et al. The multi-sleeve attachments can be simplified to 1 or 2 additional sleeves attached behind a CPT probe which would reduce their cost and maintenance requirements, and increase the ease of use by industry.

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