Multi-Sleeve Axial-Torsional-Piezo Friction Penetration System for Subsurface Characterization

Système de pénétromètre à friction axial-torsional-piezométrique à manchons multiples pour la reconnaissance des sols superficiels

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ABSTRACT: The multi-sleeve penetration system is an in-situ testing device that is derived from the cone penetration test. It incorporates a series of friction sleeves with varying surface texture along with a series of pore pressure sensors, in addition to the standard smooth friction sleeve and pore pressure sensor located directly behind the tip in the conventional CPT device. The multiple measurements made with this device allow it to provide new insight into soil type and stratigraphic variations as well as in-situ shear strengths as a function of sleeve texture height. This paper describes a third generation version of this device that incorporates torsional load sensing capabilities in addition to the standard axial load sensing capabilities. In this manner, the effects of different vertical and horizontal stress states on measured sleeve stresses can be explored. This multi-sleeve technology offers benefits over devices which are used to measure the mechanical response of soils.

RÉSUMÉ : Le système multi-manchon de pénétration est un dispositif de test in situ qui est dérivée à partir de l'essai de pénétration de cône. Il comporte une série de manchons de friction avec plus ou moins de surface le long d'une série de capteurs de pression de pore, en plus de la douille de friction lisse et standard de capteur de pression de pore situé directement derrière l'extrémité dans le dispositif de CPT classique. Les multiples mesures effectuées avec cet appareil permettent d'apporter un nouvel éclairage sur le type de sol et les variations stratigraphiques ainsi que in situ la résistance au cisaillement en fonction de la hauteur de la texture manche. Cet article décrit une version de troisième génération de ce dispositif qui intègre la charge de torsion capacités de détection, en plus de la charge axiale norme capacités de détection. De cette manière, les effets des différents états de contraintes verticales et horizontales sur les contraintes manches mesurées peuvent être explorées. Cette technologie multi-douille offre des avantages par rapport à d'autres appareils qui sont utilisés pour mesurer la réponse mécanique des sols.

1 INTRODUCTION

The general trend followed for in-situ site characterization practice has been to utilize devices that incorporate only one sensor of a given type to measure desired engineering properties. While a number of different sensor types may be incorporated into a single device, they typically measure different properties and then rely on empirical correlations to predict engineering properties. The primary reason for this single sensor approach has been historical precedent as opposed to any compelling technical limitations. While this approach has proven to yield generally acceptable results for many projects, opportunities remain to improve practice. For example, as the complexity and uniqueness of investigation projects increase, the merit of conventional single sensor in-situ tools decreases. Hence, recent efforts have sought to develop new tools for subsurface characterization studies configured with multiple sensors, which have the ability of providing more reliable information as part of more detailed investigations.

As noted above, invasive site characterization tools have traditionally followed the approach of using "single-sensor" configurations. An example is the cone penetration test (CPT). The CPT measures, as a minimum, the penetration resistance of a conical tip inserted into the ground, the frictional force that the soil exerts on a smooth sleeve located just above the cone tip, and the pore pressure (assuming the pores are fluid filled) recorded at a location also typically close to the penetrating tip as the probe is inserted into the subsurface. Such an in-situ tool can provide a robust set of data in the sense that it measures the bearing and frictional resistances of the soil being tested. However, one shortcoming is that it only measures the frictional response of the soil when sheared against a surface of fixed and specified low roughness. Studies by Frost and DeJong (2005) have shown that friction measurements of soil against smooth surfaces are more indicative of soil particle sliding along the surface and not of shearing against the sleeve surface. A more robust characterization of interface strength can be achieved when the soil is sheared against a range of surfaces of different roughnesses (DeJong et al., 2001).

2 MULTI-SENSOR IN-SITU TOOLS

Among the new generations of more specialized in-situ tools that exploit the multiple sensor approach are the "multi sleeve penetrometer attachments" developed at the Georgia Institute of Technology (DeJong, 2001; DeJong and Frost, 2002; Hebeler, 2005; Hebeler and Frost, 2006; Frost et al., 2012). These attachments are designed to be used behind a regular 15cm^2 CPT, or as a stand-alone device behind an instrumented tip. The first and second generation devices were described in detail by DeJong and Frost (2002) and Hebeler and Frost (2006), respectively, and are briefly summarized below. The third generation device is under development and is introduced herein.

2.1 First Generation: Multi-sleeve Friction Attachment (MFA). The first generation of multi sensor attachments deviates from the standard CPT in that the MFA is capable of measuring four different friction sleeve stresses in addition to the standard CPT measurements (q_t, f_s, u_2). Each sleeve position offers the possibility of being equipped with a sleeve of different roughness, with the intention of inducing different degrees of shearing in the soil. Figure 1 shows a schematic of the MFA. According to studies conducted by Frost and DeJong (2005), the standard smooth CPT friction sleeve measurement is more indicative of soil sliding against the sleeve as opposed to shearing against the soil. The reason is that the conventional CPT friction sleeves are manufactured with an intentionally smooth surface. As a consequence of the MFA's multi-sensor configuration, the device is able to determine the end bearing capacity of the soil and the relationship between interface shear strength resistance and surface texture in a single sounding. The important relationship between interface shear strength and surface roughness was originally identified through laboratory tests by Uesugi and Kishida (1986).

2.2 Second Generation: Multi-sleeve Piezo-Friction Attachment (MPFA). The second generation of multiple sensor devices offers the ability to directly measure the interface response over a range of counterface profiles, while simultaneously measuring the excess pore water pressure ahead of and after each friction sleeve as the device is advanced into the subsurface. This is achieved by means of its four independent load cells attached to the textured sleeves and five independent dynamic pore pressure sensors.

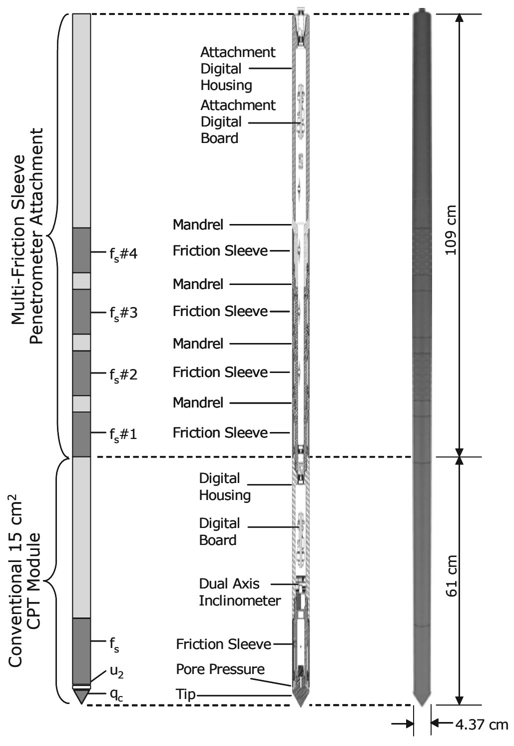

Figure 1. Schematic of the multi-sleeve friction penetrometer along with a standard CPT module.

The coupling of axial load and pore pressure sensors gives the MPFA the ability to provide a direct measure of pore water pressure generation due to shearing against surfaces of different roughnesses. Several advantages offered by the MPFA are the ability to consider the measured interface response data within an effective stress framework which is useful for applications such as liquefaction as well as strength degradation, flow and consolidation characteristics along the penetrometer's shaft, more detailed data for improved stratigraphy profiling, and the ability to distinguish between drained, undrained and partially drained conditions at the various sensor locations (Hebeler, 2005). Figure 2 shows a schematic of the MPFA. Examples of the unique insights resulting from the multi-sleeve sensor technology include in-situ determination of the relationship between interface friction and sleeve surface roughness (Figure 3) and soil classification using interface behavior (Figure 4).

3 PROPOSED SITE CHARACTERIZATION TOOL

3.1. Third Generation: Multi-sleeve Piezo-Friction-Torsion Attachment (MPFTA). The third generation of multi-sensor devices being developed at the Georgia Institute of Technology incorporates both axial and torsional shear as well as pore pressure sensing capabilities.

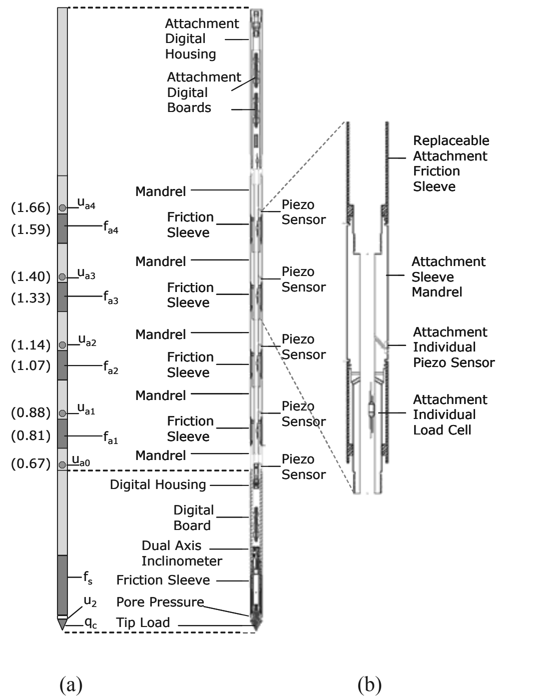

Figure 2. Schematic of the multi-piezo-sleeve friction penetrometer along with a standard CPT module (a) schematic - brackets indicate sensor offset from tip in meters and (b) piezo friction sleeve mandrel design detail.

Its dimensions and external characteristics, with and without pore pressure sensing capabilities, are similar to the MFA and MPFA shown in Figures 1 and 2, respectively. However, the new concept incorporated into the device consists of a dual load-torsion cell being installed in each sleeve module and location, with the goal of measuring both axial and torsional shear responses of the soil throughout the same sounding. In this manner, the effects of special variability (vertical and horizontal) will be eliminated and more detailed information about the soil's anisotropy and state of stress can be provided. The proposed texture of the MPFTA's friction sleeves is the same to the texture of the MFA and MPFA's sleeves as shown in Figure 5. The friction sleeve texture pattern consists of machined diamond shaped features with a height that typically ranges from 0.25 to 2 mm in order to induce different degrees of shearing. The configuration of penetration angle, diamond width, diagonal spacing, texture slope and areas with no textural features ensures that shearing is induced with the soil and prevents clogging of the textural features.

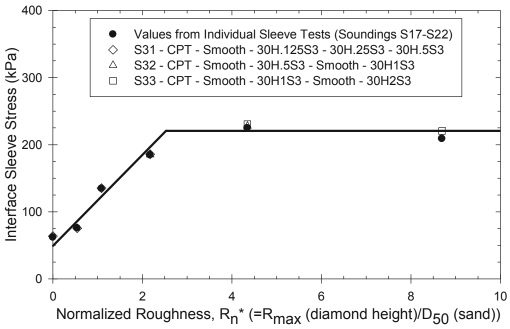

Figure 3. Relationship between surface roughness and interface friction determined using multi-sleeve technology.

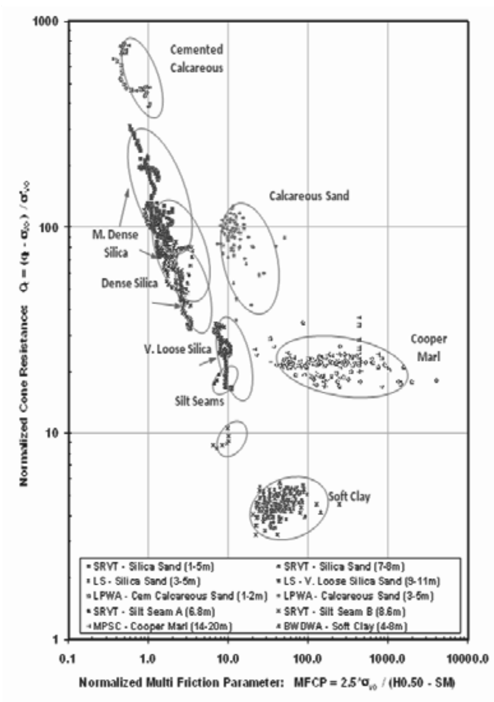

Figure 4. Soil Classification Chart based on multi-sleeve data.

3.1 Comparison to Existing In-Situ Testing Systems. The MPFTA device has relatively little in common with the in-situ shear vane test. The shear vane is typically used to characterize the response of soft clays. The reason is that stiffer soils can compromise the structural integrity of the shear vane, resulting in blade bending. It is considered that this is not a limiting factor for the MPFTA's frictional elements because of their different design and thus stiffer configuration. It is important to note that the MPFTA's intent is to the surface interface strength of the soil in the axial and radial directions, while the shear vane's intent is to measure the soil's undrained shear strength. Finally, as shown by Chandler (1988), different diameter sizes can impose strain-rate effects; however since the diameter of the MPFTA device is constant and only the height of the diamond texture elements changes, the results of the MPFTA will not need to be corrected for this and other potential geometry effects.

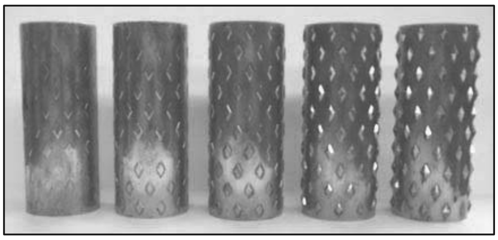

Figure 5. MFA and MFPA's friction sleeves with increasing diamond height (from left to right)

3.2 Sleeve Locking Mechanism. For the MFA and MPFA devices, the axial force is derived from measurements using a series of bonded strain gauges configured as the four-branches of a wheatstone bridge. Application of the soil shear force on the textured sleeves brings them into contact with a "shoulder" and the resulting change in length of the bonded strain gauges changes the output of the Wheatstone bridge. In order to measure the torque applied when the sleeve is rotated, the sleeve is temporarily fixed to the core of the mandrel by an electromagnet which prevents rotation of the sleeve and instead induces changes in resistance of a set of orthogonally bonded strain gauges also configured as the branches of a Wheatstone bridge. Given the magnitude of the forces on even the most heavily textured sleeves, relatively low currents are required to "lock" the electromagnets and thus sleeves during torsional testing. A sketch and photograph showing the axial and torsional load application modes for the new device are shown in Figure 6. Final designs of the actual combined axial-torsional cell are being completed. Once measurements at a given sounding elevation are completed, the electromagnets are turned off and the penetration of the device and recording of axial loads is continued. In many instances, the device will be advanced so that a sleeve is advanced to the same elevation that the adjacent preceding sleeve was located at in a previous torsional test so that successive torsional test measurements are made at the same elevations with sleeves of increasing texture height. This eliminates the need to account for lateral and vertical variability since successive tests are performed on the same material.

4 CONCLUSIONS

Significant advances have been made in the last four decades in the design, use and interpretation of the results from penetrometer devices used for subsurface characterization. Similarly, over the past two decades, significant new insight has been developed into the role of surface roughness on the behavior of geotechnical interfaces. An emerging family of innovative devices has been developed in the last decade that leverages the advances in performance of penetrometer devices with the new understanding of interface behavior to produce multi-sleeve devices that allow for direct in-situ determination of the relationship between surface roughness and interface shear as well as the development of shear induced pore pressures when surfaces of various roughness are sheared against soils. A unique aspect of this family of devices is the use of multiple friction sleeves with surface of different roughness in the same sounding so that the effects of material variability can be isolated and/or eliminated. To date, all these devices rely on response of soils during axial penetration.

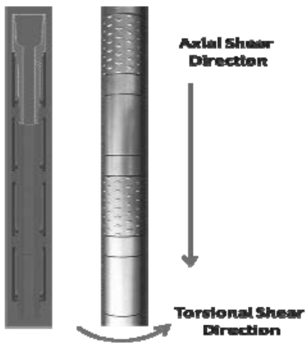

Figure 6. Schematic and photograph of multi-sleeve piezo- friction-torque penetrometer showing load application modes.

This paper describes the development of a new device that embodies the attributes of the existing multi-sleeve devices but incorporates the ability to also conduct torsional friction penetrometer tests in the same sounding. In contrast to existing vane shear type devices which involve the application of a torsional force to a rigid central shaft and measure the resistance to rotation of a set of blades in a soil, the new device enables measurement of torsional resistance with the same textured sleeves used in the axial stage of the test. This is possible through the use of an innovative electro-mechanical system that allows independent measurements of axial and torsional resistance of the sleeves of the penetrometer device. The availability of complimentary axial and torsional shear forces along with the associated pore pressures generated by friction sleeves of different surface roughness represents a potential "disruptive technology" in the in-situ characterization of soil properties ranging from soil type to soil strength and deformation properties to assessment of the in-situ state of stress and associated parameters such as the in-situ stress ratio. Significant opportunities exist for dramatic advances in subsurface investigation. Single sensor historical precedent has guided the design and configuration of in-situ devices, there are clear advantages to developing multiple sensor systems for future investigation studies.

The recent development of various configurations of multi-sensor systems including the previously presented generation 1 MFA and generation 2 MPFA as well as the proposed generation 3 MPFTA device introduced herein represent a significant departure from traditional practice. Amongst the benefits of the latter device are:

i) Up to sixteen independent measures of interface shear ranging from smooth surface sliding to textured surface soil shearing can be realized in a single sounding in contrast to the three measures possible with conventional cone penetration systems.

ii) The effects of different vertical and horizontal stress states on measured sleeve stresses can be accounted for by means of the axial and torsional interface stress response.

iii) The procedure for performing combined axial-torsional-piezo penetration testing of the subsurface using the proposed MPFTA system involves a series of steps which allows them to be readily controlled from a remote location and to be performed using robotic systems.

5 ACKNOWLEDGEMENTS

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