A new multi-friction sleeve attachment

Un nouvel appareil pour le resistance des interfaces

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ABSTRACT: Critical elements in most geotechnical systems are the interfaces between soils and other man-made geomaterials. Despite widespread recognition of this fact, little progress has been made in developing field techniques that can be used to predict the interface friction or strength. This paper describes the fundamental rational behind the development of a new device that can be used to measure interface strength in situ while accounting for the roughness of the geomaterial counterface. An overview of the device is presented along with example results from field testing that directly show the importance of measuring interface strength with a surface whose roughness is representative of what the prototype system will include.

RÉSUMÉ: Les interfaces entre le sol et les autres materiaux naturels ou construits sont des elements critiques d'un systeme geotechnique. Bien que ce fait soit largement reconnu, peu de progres ont ete faits pour developper des techniques applicables sur le terrain, en vue de determiner les caracteristiques de frottement ou de resistance des interfaces. Cet article decrit les bases rationnelles sur lesquelles un nouvel appareil a ete developpe afin de mesurer, in situ, la resistance des interfaces, en prenant en compte la rugosite de surface des geomateriaux. Un apercu de l'appareil est presente, ainsi que les resultats tires d'exemples d'essais sur le terrain. Ceux-ci montrent bien l'importance des mesures de resistance d'interface avec une surface dont la rugosite est representative de celle qui sera presente dans le systeme reel.

1 INTRODUCTION

Measurements currently obtained with the cone penetration test (CPT) friction sleeve are less widely used than those obtained with the tip. The "underuse" of the friction sleeve data results from the common sentiment that the measurement is unreliable. A primary factor that has been identified as significantly affecting the measurement but has not been fully understood to date is surface roughness. To gain further insight into this issue, a multi-friction sleeve attachment has been developed. Key characteristics of the attachment include the ability to make four independent f_s measurements at each elevation in a sounding in addition to the conventional CPT measurements. This allows for direct in-situ assessment of the effect of surface roughness while eliminating soil variability as all measurements are recorded at the same elevation within a single sounding.

The behavior at interfaces is typically estimated using empirical approaches that depend on appropriate engineering judgment being made regarding numerous key issues including subsurface variability, state of stress, and effect of geomaterial surface roughness among others. Clearly, improvement in the ability to accurately predict the behavior of soil-geomaterial interfaces can lead to more efficient geotechnical structure designs. To this end, the new multi-friction sleeve penetrometer attachment that enables direct insitu measurement of interface strength has potential. This can eliminate the need for empirical adjustment factors currently required in estimating interface strength.

The multi-friction sleeve device is typically attached behind a conventional 15 cm^2 CPT, allowing for simultaneous measurements of conventional CPT sensors (e.g. q_c, f_s, and u_2) in addition to the multi-sleeve attachment measurements. For certain applications, non-instrumented tips of varying length can be used in place of a conventional CPT module with the new penetrometer attachment.

2 ROLE OF SURFACE ROUGHNESS

As shown by Uesugi and Kishida (1986) and others, small changes in the surface roughness can result in substantial changes in interface strength (Figure 1). Consequently, the surface roughness of insitu devices whose measurements are directly dependent on the interface conditions, such as the CPT friction sleeve, should be monitored closely. The importance of changes in surface roughness is clearly evident through consideration of the potential effect of changes in the conventional smooth friction sleeve surface roughness due to regular use on the CPT f_s measurement. ASTM D3441 (1994) and ISSMFE (1989) standards for the CPT specify that the friction sleeve roughness, R_a (average roughness), must be equal to 0.50 ± 0.25 µm. Surface roughness measurements performed by the authors

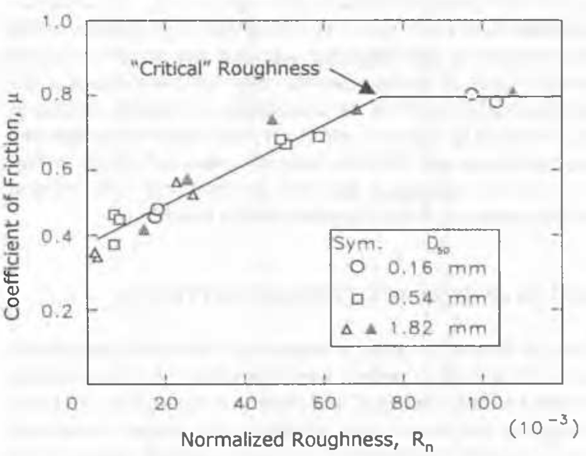

Figure 1. Relationship Between Surface Roughness and Interface Friction (after Uesugi and Kishida, 1986).

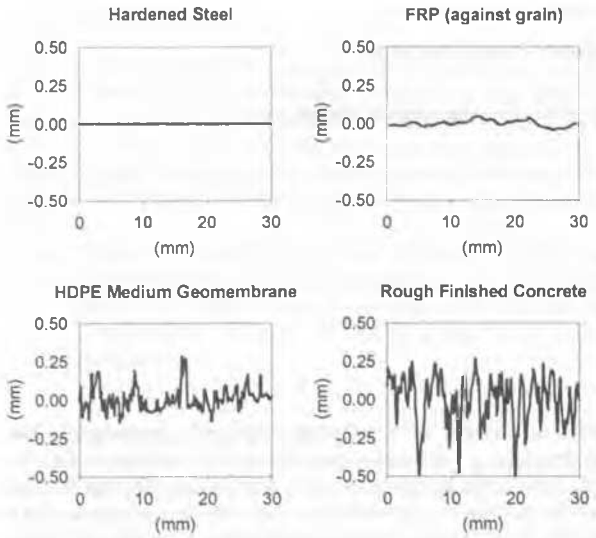

Figure 2. Surface Profiles of Selected Geomaterials.

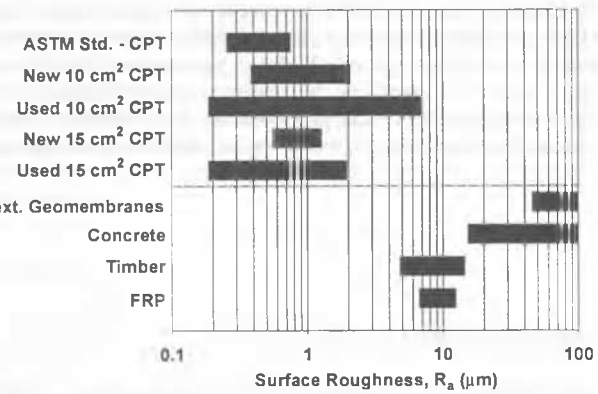

Figure 3. Average Surface Roughness Values for New and Used CPT Sleeves and Selected Geomembranes.

with a stylus profilometer along the axis of a set of 10 and 15 cm^2 friction sleeves, following shipment from the manufacturer as well as throughout their service life, showed that the actual surface roughness values range between 0.28 to 2.08 μm for new sleeves and between 0.18 to 6.85 μm for used sleeves (DeJong et al. 2000). These observations indicated that a majority of the CPT soundings are currently performed with the friction sleeve surface roughness outside specified standards. Equally importantly, similar surface profile measurements performed on a range of man-made geomaterials used in foundation systems (Figure 2) show these materials have significantly different surface profiles from each other. Of even greater significance is that when compared to the suggested standard and actual measured roughness values of friction sleeves, they have significantly different characteristics. From the comparison of surface roughness values presented in Figure 3 and the typical relationship between surface roughness and interface strength presented earlier in Figure 1, it is not surprising that the conventional CPT friction sleeve measurement is not considered to be reliable.

3 DESIGN OF SURFACE TEXTURE PATTERNS

Through laboratory tests, a number of desirable characteristics of a sleeve texture pattern were identified. A sleeve texture that would be "self-cleaning" and thereby not result in soil particles clogging the texture and changing the surface roughness during a sounding was desired. This was essential, especially for layered soil profiles, where soil particles from one layer could be carried into lower soil layers when trapped in the surface texture. At the same time, texturing which would induce internal shearing of the soil rather than only sliding of soil particles along the interface was required. It was clear that a surface that consisted of a flat base substrate with peak features extending above it would be preferable to control the surface roughness and prevent clogging. Further, the surface design had to enable machining of textured sleeves that encompass the range of surface roughness values for conventional geomaterials.

The texturing patterns selected for use with the penetrometer attachment were based on a staggered diamond configuration. The average surface roughness (R_a) values for the diamond textured sleeves ranged from 0.05 to 240 μm. The variations of the staggered diamond pattern included varying the height (H) from 0.25 to 2.0 mm, the diagonal spacing (S) from 4.6 to 12.5 mm, and the penetration angle (β) from 30 to 120 degrees. Each sleeve was machined so that the base diameter equaled the diameter of a conventional smooth sleeve (44.09 ± 0.05 mm) and the diamond pattern extended beyond that surface.

A total of 15 different diamond textured attachment sleeves in addition to the conventional smooth sleeve were manufactured and tested. It is noted that the roughness values presented were calculated based on the repeating geometric pattern in three dimensional formulations since the diamond patterns induce soil shearing around the diamonds.

4 MULTI-FRICTION SLEEVE ATTACHMENT

The multi-sleeve penetrometer attachment allows for four individual measures of interface strength at each measurement elevation throughout a sounding. This was accomplished by positioning four independent load-sensing modules that have replaceable sleeves in series. Additionally, the penetrometer attachment was intentionally designed to be compatible behind a conventional 15 cm^2 CPT module. As mentioned, with the conventional CPT gaining wide acceptance in practice, it was considered important not to alter the standard CPT configuration and thereby set back the progress already made. A photo of the manufactured penetrometer attachment and a conventional CPT module are shown in Figure 4. In its final design, the multi-friction sleeve attachment is 109 cm in length including the digital housing and the conventional CPT module is 61 cm in length resulting in a total instrument length of 170 cm.

As previously noted, the attachment was designed so that it could be readily assembled behind a conventional CPT module. It was envisioned that this would be the standard configuration used for a majority of soundings. In this configuration, conventional CPT q_c, f_s, and u_2 measurements can be obtained in the same sounding and provide the opportunity to compare the penetrometer attachment measurements with standardized insitu measurements. This configuration was extremely useful in the initial validation stage as it enabled rapid identification of the subsurface stratigraphy encountered in each sounding and separation of the differences due to lateral variability from those due to changes in sleeve texture.

In the design of the first prototype, it was considered important that the attachment permitted efficient disassembly/reassembly between soundings and that modifications could be made with minimal adjustments. This resulted in a jointed mandrel design whereby each individual load cell unit (mandrel, load cell, and sleeve) is comprised of separate components. The jointed mandrels for f_s*#1*, f_s*#2*, and f_s*#3* are identical while the f_s*#4* mandrel has a different female connection at the top to allow for connection with the digital housing. With this modularity, the number of different custom components was minimized and a damaged load cell unit could be easily replaced with a backup unit in the field. During validation testing, this design allowed

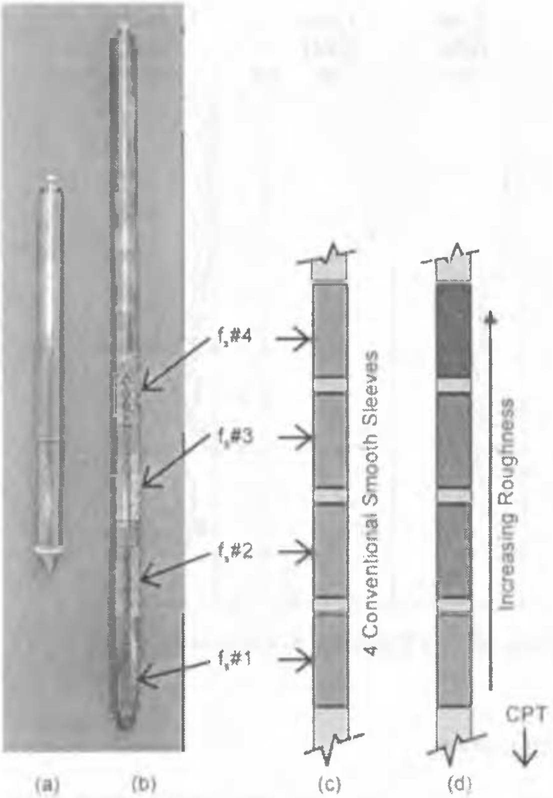

Figure 4. (a) Conventional CPT Module (b) Multi-Friction Sleeve Attachment (c) Four Conventional Smooth Sleeve Configuration (d) Increasing Roughness Sleeve Configuration.

for complete disassembly, cleaning, sleeve replacement, and reassembly between soundings in about twenty minutes. A modular design was considered preferable since modifications to individual load cells could be performed with relative ease.

A data acquisition system that allowed for real-time review of data as with conventional CPT systems was developed. The CPT module used in this study incorporated the hardware to measure the q_c, f_s, and u_2 values and the penetrometer attachment incorporated the hardware to individually measure the force on each of the four sleeves ($f_s\#1$, $f_s\#2$, $f_s\#3$, and $f_s\#4$) at each measurement increment. In addition, a dual axis inclinometer system was incorporated in the CPT module to enable verticality during penetration to be continuously monitored. Penetration depth was monitored up-hole using a wireline potentiometer. With nine individual measurements being obtained downhole by the complete CPT and attachment system, a down-hole analog-to-digital signal conditioning system was developed. To maintain the independence of the CPT module, the CPT analog signals were conditioned and converted to digital signals separately within the CPT housing. The attachment signals were conditioned in a similar fashion and then multiplexed with the digital signals from the CPT and relayed up-hole to the data acquisition system.

5 DEVICE CALIBRATION

A series of calibration tests were performed to assess the performance of the multi-friction sleeve attachment system. Prior to assembly of the penetrometer attachment, each load cell was calibrated individually without signal conditioning against a NIST traceable load cell by applying an excitation directly to the full bridge and monitoring the output during a load – unload cycle. All calibration factors had R^2 values of 0.9999 or higher and the nonlinearity for all factors was 0.15% of the full scale output (45 kN) or less.

Recalibration of each attachment load cell was undertaken in the fully assembled CPT – attachment configuration with the data acquisition system. Again, each attachment load cell underwent a load – unload cycle against a NIST traceable load cell. During calibration, all four attachment load cells were monitored through the data acquisition system. This enabled both the calibration of each load cell through the signal conditioning system as well as assessment of mechanical cross-talk between the multiple sleeve load cells. The calibration factors of the fully assembled penetrometer system were very similar to those obtained with isolated direct calibration method presented above with the R^2 values for all load cells being above 0.999. Minimal mechanical cross-talk (less than 0.2% of the applied load) was observed to occur between the load cell being calibrated and the other load cells behind it. Load cells in front of the cell being calibrated did not experience any cross-talk. For example, when $f_s\#2$ was calibrated, $f_s\#3$ and $f_s\#4$ experienced minimal mechanical cross-talk while $f_s\#1$ did not experience any cross-talk.

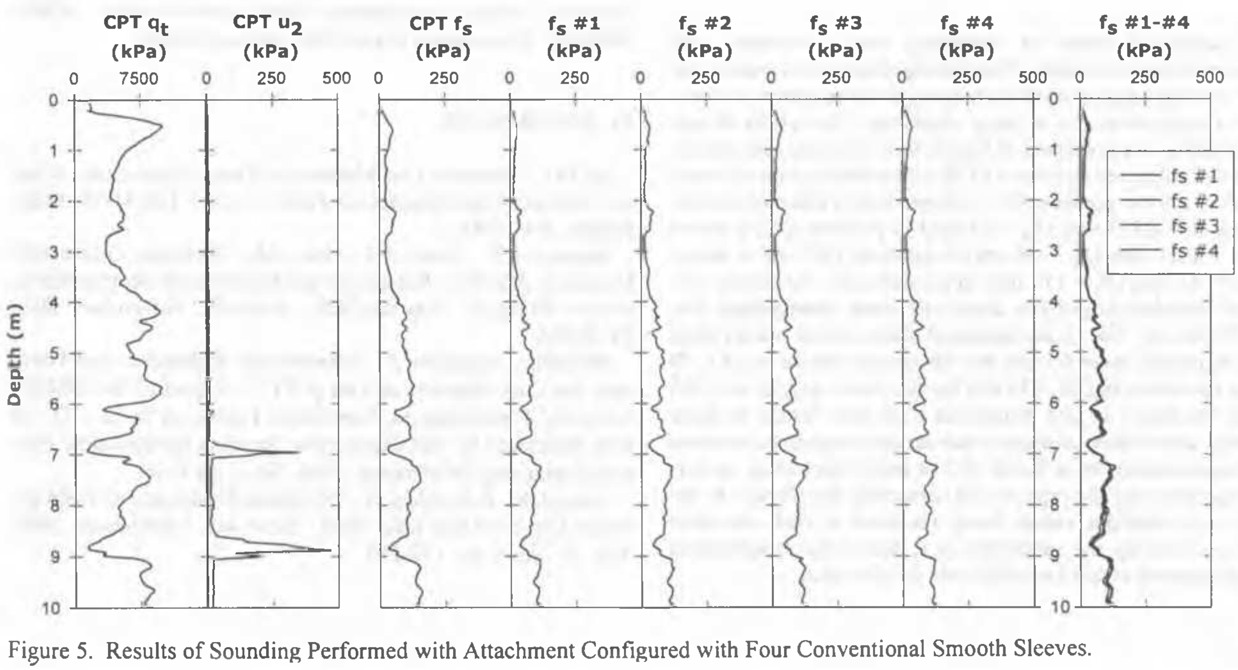

Figure 5. Results of Sounding Performed with Attachment Configured with Four Conventional Smooth Sleeves.

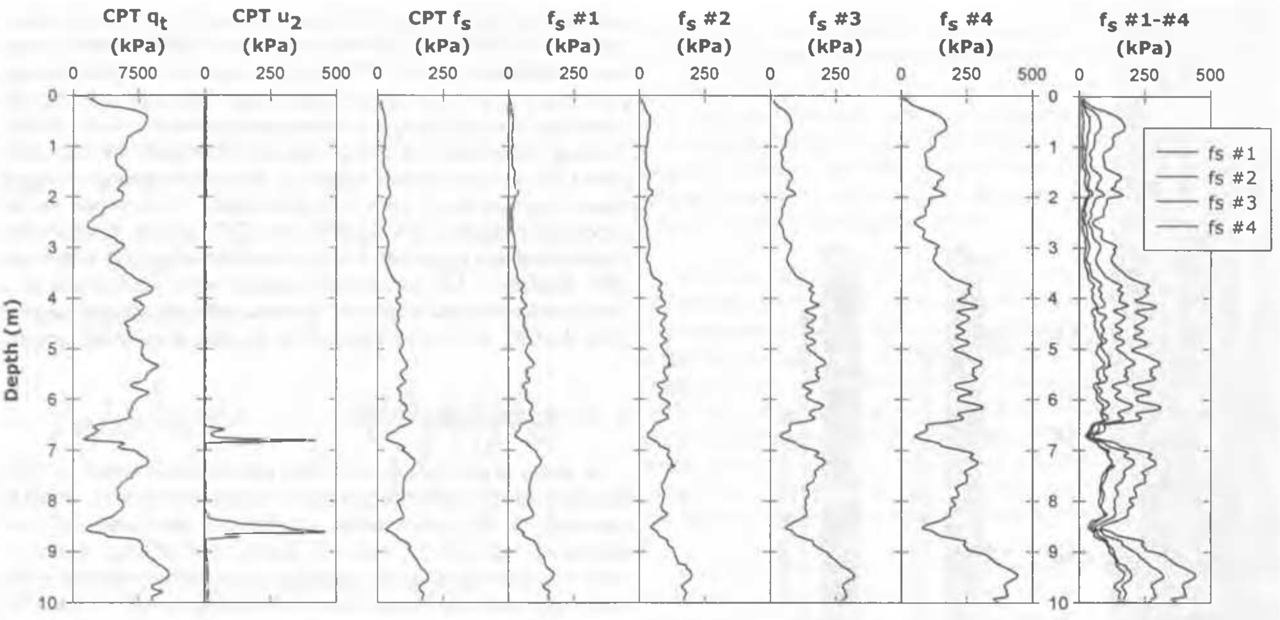

Figure 6. Results of Sounding Performed with Attachment Configured with Sleeves Positioned in Order of Increasing Roughness.

6 SOUNDINGS WITH SMOOTH SLEEVES

An initial series of soundings was performed with four conventional smooth sleeves (Figure 5) to assess the operational performance of the multi-friction sleeve attachment. The CPT q_c and u_2 profiles are plotted to the left followed by the conventional CPT f_s measurement. The four attachment friction sleeve profiles are plotted to the right of the CPT f_s profile in order of position with f_s#1 being the attachment sleeve closest to the cone and f_s#4 being the attachment sleeve farthest from the cone. At the extreme right of the plot, the four attachment f_s profiles are plotted together. It can be seen that a very high level of repeatability is obtained. More importantly, these tests confirmed that a constant reference baseline with essentially no degradation in measured sleeve force is obtained when multiple conventional smooth sleeves are used in series.

7 SOUNDINGS WITH TEXTURED SLEEVES

An additional series of soundings were performed with sleeves positioned in order of increasing roughness to assess the ability to obtain multiple interface strength measurements over a range of roughnesses in a single sounding. The results of one such sounding are presented in Figure 6. In this case, the attachment was configured with an ASTM conventional smooth sleeve (R_a = 0.50 μm) in position f_s#1, a sleeve with a diamond texturing with H = 0.125 mm (R_a = 35 μm) in position f_s#2, a sleeve with H = 0.25 mm (R_a = 66 μm) in position f_s#3, and a sleeve with H = 0.5 mm (R_a = 117 μm) in position f_s#4. As clearly evident, all attachment profiles detect the same stratigraphic features (Figure 6). The mean measured sleeve stress values from linear regression were 65 kPa for the smooth sleeve in f_s#1, 79 kPa for the sleeve in f_s#2, 134 kPa for the sleeve in f_s#3, and 204 kPa for the sleeve in f_s#4. Numerous field tests similar to those described above have confirmed that surface roughness increases the f_s measurement by a factor of 3 or more, depending on surface roughness and the type of soil contacting the sleeve. In addition, with multiple values being recorded at each elevation within a sounding, the variability of f_s due to the measurement error as opposed to soil variability can be identified.

8 CONCLUSIONS

This paper has described a new multi-friction sleeve attachment for the cone penetrometer. The importance of accounting for surface roughness in interface strength measurements was discussed. The design and operation of the new device has been presented along with the results of initial field tests conducted using conventional smooth friction sleeves as well as custom designed textured sleeves. The device is considered to have the potential to make significant contributions in geotechnical systems that are heavily dependent on interface friction mechanisms for proper performance include deep foundations, synthetic impervious liners, trenchless technologies, and earth retaining structures.

9 ACKNOWLEDGEMENTS

The work performed in this study has been supported by the National Science Foundation under grant number #CMS-9978630. This support is gratefully acknowledged.

10 REFERENCES

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