Canadian Geotechnical Journal

OPEN ACCESS | Note

Deepwater soil investigation using a free fall penetrometer

Nina Stark[a], **Nico Parasie**[b], **and Joek Peuchen**[b]

[a]Charles E. Via, Jr. Department for Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, USA; [b]Fugro, Nootdorp, The Netherlands

Corresponding author: **Nina Stark** (email: ninas@vt.edu)

Abstract

Free fall penetrometers (FFP) can improve the efficiency of deepwater geotechnical site investigations. This study investigates the derivation of geotechnical properties from piezocone FFP measurements in the upper 4 m of the seabed at a clayey site with water depths of ~1500 m. Data analysis methods as commonly applied in cone penetration test (CPT) analysis were tested with strain rate normalization methods previously suggested for FFP analysis. The logarithmic, inverse hyperbolic sine, and power law approaches were applied for strain rate normalization. Strain rate effects appeared small for FFP cone resistance (with $\mu = 0.1$ for the logarithmic and $\beta = 0.06$ for the power law approach), but were apparent. Undrained shear strength derived from FFP data matched overall the CPT results, using an N factor $N_{kt} = 12$. Undrained shear strength derived from excess pore pressure measured at the u_1 position also yielded favorable results using $N_{\Delta u\_FFP} = 6$. Two soil behavior type classifications showed acceptable agreement between strain rate normalized FFP and CPT results.

Key words: free fall penetrometer, cone penetration test, deepwater, undrained shear strength, soil behavior type, strain rate

Résumé

Les pénétromètres à chute libre (FFP) peuvent améliorer l'efficacité des investigations géotechniques en eaux profondes. Cette étude examine la dérivation des propriétés géotechniques à partir des mesures de la FFP du piézocône dans les 4 m supérieurs du fond marin sur un site argileux avec des profondeurs d'eau de ~1500 m. Les méthodes d'analyse des données telles qu'elles sont couramment appliquées dans l'analyse du test de pénétration du cône (CPT) ont été testées avec des méthodes de normalisation de la vitesse de déformation suggérées précédemment pour l'analyse FFP. Les approches logarithmiques, sinus hyperboliques inverses et lois de puissance ont été appliqués pour la normalisation de la vitesse de déformation. Les effets de la vitesse de déformation semblent faibles pour la résistance du cône FFP (avec $\mu = 0.1$ pour l'approche logarithmique et $\beta = 0.06$ pour l'approche de la loi de puissance), mais étaient apparents. La résistance au cisaillement non drainée dérivée des données FFP correspondait globalement aux résultats du CPT, en utilisant un facteur N, $N_{kt} = 12$. La résistance au cisaillement non drainée dérivée de l'excès de pression interstitielle mesuré à l'endroit où se trouve l'échantillon u_1 a également donné des résultats favorables en utilisant $N_{\Delta u\_FFP} = 6$. Deux classifications du type de comportement du sol (SBT) ont montré une concordance acceptable entre les résultats de la FFP et du CPT normalisés par la vitesse de déformation. [Traduit par la Rédaction]

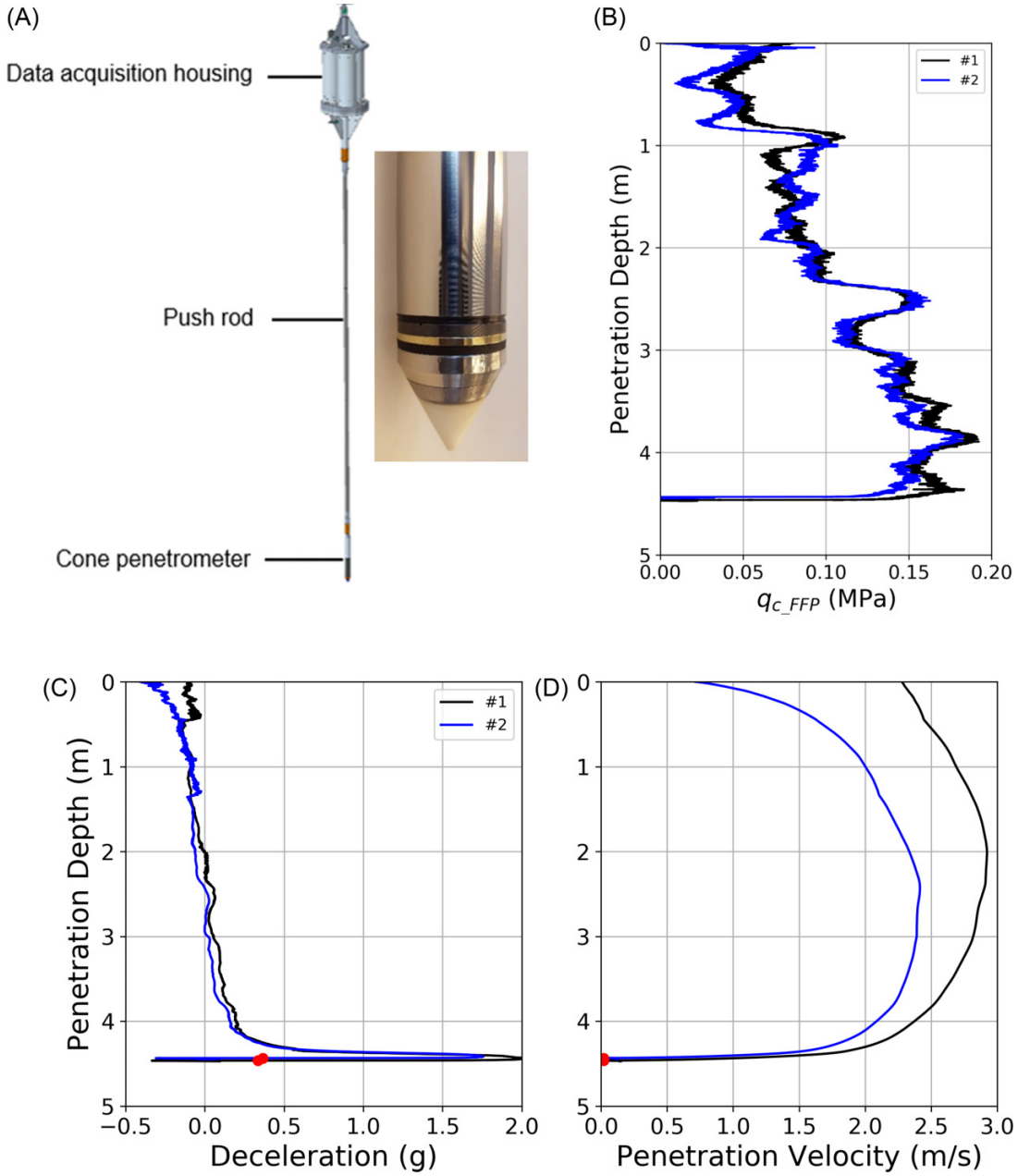
Mots-clés : pénétromètre à chute libre, essai de pénétration au cône, eau profonde, résistance au cisaillement non drainé, type de comportement du sol, taux de déformation

1. Introduction

Marine site investigations are an important part of offshore engineering and construction activities (ISO 2014). Randolph et al. (2018) suggested the free fall penetrometer (FFP) as a cost-effective means for near-surface seabed characterization. They highlighted specifically the relevance of the FFP for deepwater environments. However, few data sets are available offering a direct comparison between FFP and standard Cone Penetration Testing (CPT), particularly from deepwater environments.

This paper presents a case study of two FFP deployments close to a CPT profile and soil sample data at a deepwater (~1500 m) site in the Mediterranean Sea. An initial data quality assessment with emphasis on the deployment method has been presented by Stark et al. (2021). Here, profiles of undrained shear strength s_u versus depth and soil behavior type (SBT) charts such as the Robertson (2016) charts are targeted. Strain rate effects resulting from the significant higher penetration velocity of the FFP compared with CPT (here about 100 times faster) are addressed using the ap-

Fig. 1. FFP configuration (A), cone resistance (B), deceleration (C), and velocity (D) measured by the FFP for the full penetration depth. [Colour online]

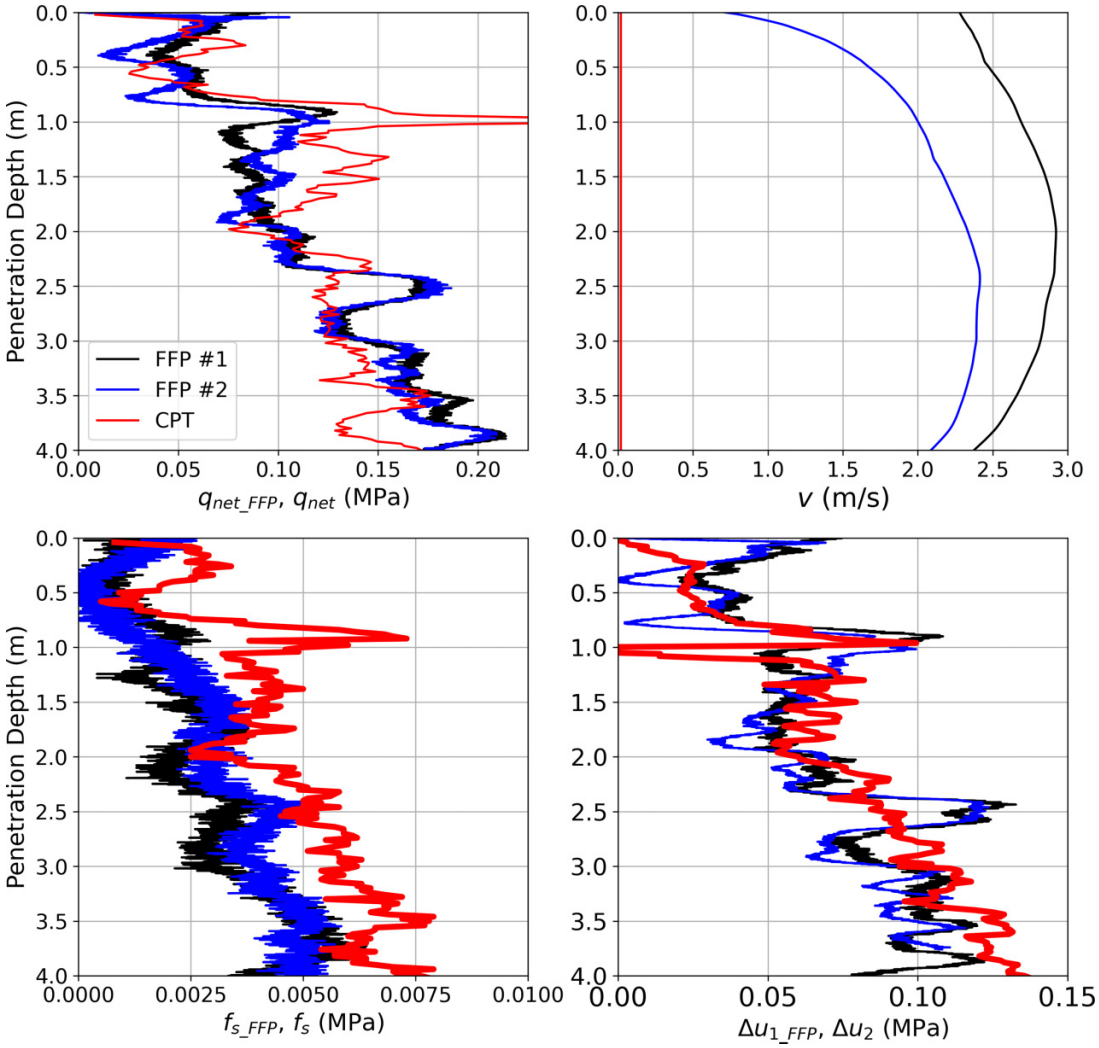


proaches suggested by Steiner et al. (2014) and Chow et al. (2017). The choice of N factors followed Chow et al. (2017) and suggestions from CPT following Mayne and Peuchen (2018).

2. Methods and site conditions

The FFP SEADART 1 consists of a data acquisition and battery housing, a CPT-typical piezocone penetrometer, and push rods connecting them both (Fig. 1A). The piezocone has a cross-sectional area of 1500 mm^2 and a net area ratio of $a = 0.82$. The geometry of the cone penetrometer is in line with ISO (2014). The piezocone measures cone resistance, sleeve friction, pore pressure in the u_1 position (i.e., on the cone face, Fig. 1A), and inclination. The FFP penetration depth was 4.4 m for both deployments with measured FFP inclinations < 5° from vertical. Figures 1B–1C show the measured cone resistance, q_{c_FFP}, and deceleration throughout the penetration of the two deployments. At a penetration depth of >4 m, q_{c_FFP} decreased somewhat while the FFP was rapidly decelerated. The rod length during these deployments was 4 m and therefore, it can be assumed that the widening of the penetrometer diameter associated with the data acquisition housing led to the stop of the FFP past a penetration depth of 4 m (Fig. 1). Therefore, results are reviewed for a penetration of 4 m (Figs. 2–5). Figure 1D presents the FFP velocity during penetration for both deployments. The reader is referred to Peuchen et al. (2017) and Stark et al. (2021) for a detailed dis-

Fig. 2. Net cone resistance, q_{net_FFP} and q_{net}; velocity, v; sleeve friction, f_{s_FFP} and f_s measured by FFP and CPT, respectively, and excess pore pressure measured at u_1 by the FFP and at u_2 by the CPT. [Colour online]



cussion on the ancillary sensor suite including multiple sets of accelerometers.

CPT data were acquired to 15 m penetration depth, in non-drilling mode according to ISO (2014). CPT Application Class 1 is assessed to apply. From piston core (diameter, 0.1 m) sampling, the soil was described as very soft to firm calcareous fat clay with occasional organic matter to depths well below FFP penetration. Table 1 provides laboratory test results for the depth range of interest. The undrained shear strengths were derived from miniature vane tests.

Data processing of the FFP followed overall the procedure described by Chow et al. (2017). Three strain rate correction methods were applied (Steiner et al. 2014; Chow et al. 2017). These methods express strain rate correction based on a logarithmic, an inverse hyperbolic sine, and a power law. For the derivation of s_u from the FFP-corrected net cone resistance, $N_{kt} = 12$ was applied following Mayne and Peuchen (2018) and considering the local soil type. Additionally, s_u was derived from excess pore pressure following Esrig et al. (1977) and Stegmann et al. (2006) using a CPT-based N factor $N_{\Delta\ u\_FFP} = 6$. Finally, the updated Schneider et al. (2008) SBT chart following Robertson (2016) was tested for FFP application. The detailed data processing procedure is provided in the supplementary materials.

3. Results and discussion

Figure 2 shows the significant difference in penetration velocity between FFP and CPT. Net cone resistance, q_{net_FFP}, q_{net}, showed agreement between FFP and CPT in the uppermost 0.6 m of the seabed, despite the velocity difference (Fig. 2). At penetration depths between 0.6 and 2 m, both CPT and FFP suggested the presence of a stiffer layer, but with the CPT showing a significant peak in strength that was not registered by the FFPs. This may be related to local seabed inhomogeneities. Below a penetration depth of 2 m, the CPT measured slightly smaller q_{net}, in line with expectations from strain rate effects (Steiner et al. 2014; Chow et al. 2017). The FFP suggested slightly smaller sleeve friction than the CPT throughout the penetration (Fig. 2), opposing previous suggestions regarding strain rate effects on sleeve friction (Steiner et al. 2014; Chow et al. 2017). However, sleeve fric-

Fig. 3. Undrained shear strength estimated from FFP deployments #1 (left) and #2 (right) for selected strain rate normalizations and using a N factor of $N_{kt} = 12$ for both FFP and CPT. [Colour online]

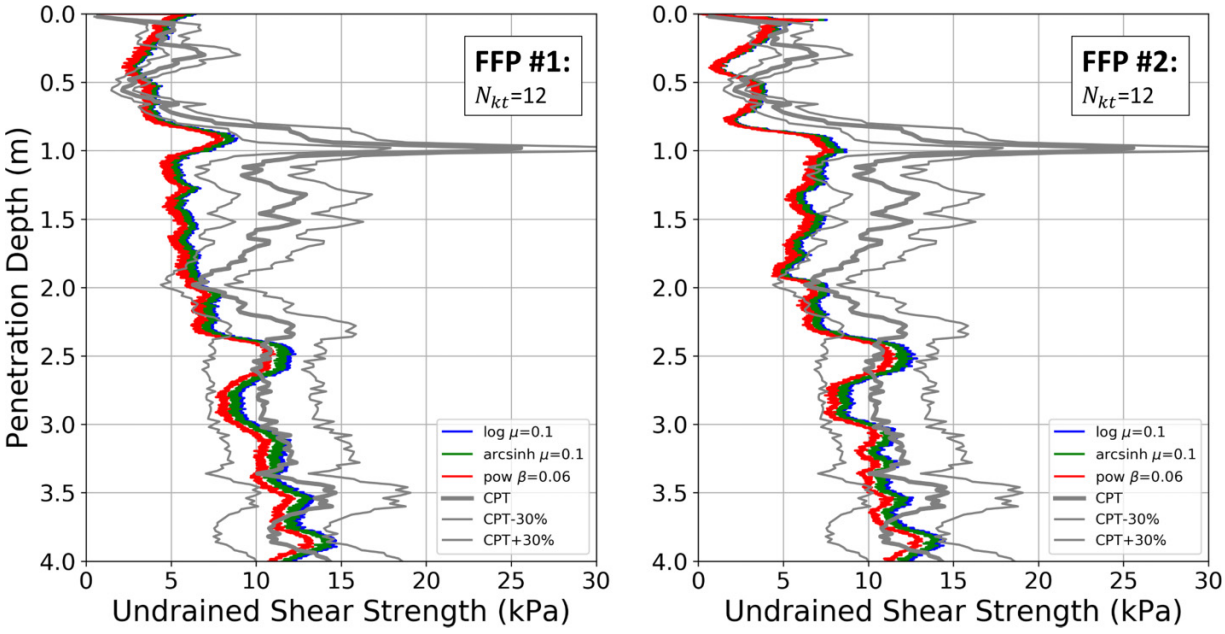


Fig. 4. Undrained shear strength estimated from excess pore pressure of both FFP deployments and the CPT using N factor $N_{\Delta u\_FFP} = N_{\Delta u} = 6$, and undrained shear strength derived from net cone resistance of the CPT with N factor $N_{kt} = 12$. [Colour online]

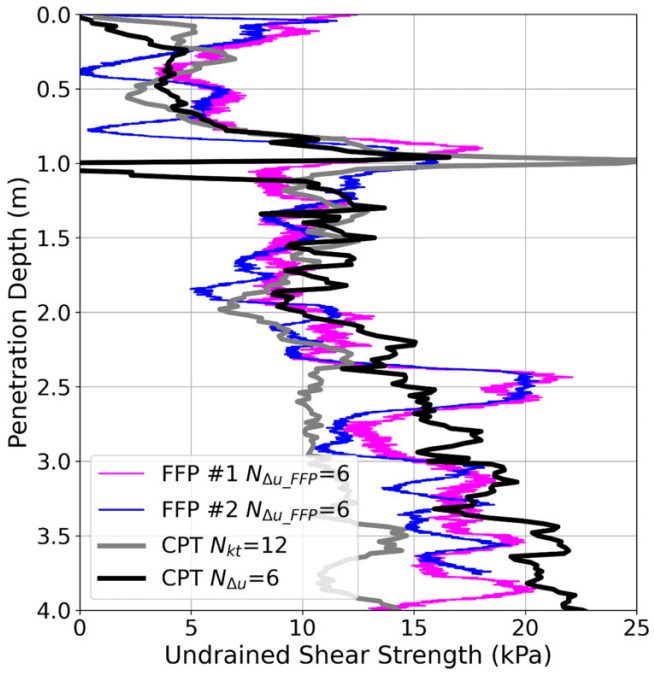
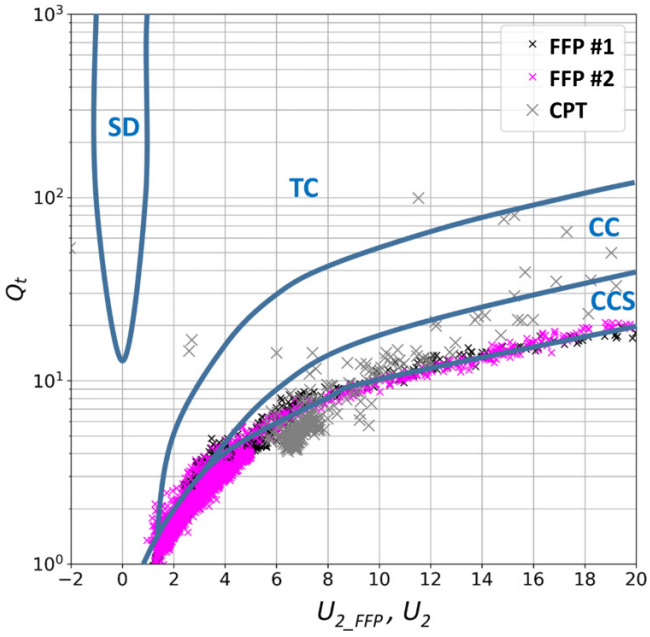


Fig. 5. FFP and CPT results applied to the modified Schneider et al. (2008) SBT chart after Robertson (2016). Values of FFP Q_t calculated with a logarithmic strain rate normalization of $\mu = 0.1$. Soil behavior types are defined in this chart as "SD" being essentially drained sands, "TC" being transitional soils, "CC" being clay-like contractive soils, and "CCS" being clay-like contractive soils with high sensitivity. [Colour online]



tion measurements were generally low for all measurements with differences being mostly within uncertainty of the measurement (Peuchen and Terwindt 2014). FFP excess pore pressure measurements, Δu_{1_FFP}, show an overall agreement between the two deployments (Fig. 2). Furthermore, comparison with CPT Δu_2 suggests $\Delta u_{1\_FFP} \approx \Delta u_2$, with deviations at the seafloor where the FFP immediately experienced a significant increase in Δu_{1_FFP}, not shown in Δu_2. These deviations

Table 1. Geotechnical properties of piston core samples at the depths of interest.

Depth (m BSF)	Unit weight (kN/m^3)	Water content (%)	Liquid limit (%)	Undrained shear strength (kPa)
0	15	85	—	2
0.8	15	85	90	2
1.7	15.5	65	80	4
2.7	15	80	—	9
3.7	15.5	80	70	7

are likely associated with the high velocity impact versus the significantly slower and gentler CPT penetration, as well as the differences in piezocone filter positions, u_1 versus u_2. The observation $\Delta u_{1\_FFP} \approx \Delta u_2$ is somewhat surprising considering the differences in sensor location (e.g., Peuchen et al. 2010) and penetration velocity. At this time, further investigations are needed to fully understand the governing processes regarding correction of strain rate effects of FFP pore pressure measurements (e.g., Chow et al. 2017; Mumtaz et al. 2018) and the associated effects on relationships between Δu_{1_FFP}, $\Delta u_{2\_FFP,}$ and Δu_2. This initial study will apply $\Delta u_{1\_FFP} \approx \Delta u_2$ based on the observations shown in Fig. 2.

Figure 3 illustrates s_u derived from q_{net} normalized to a velocity $v = 0.02$ m/s, with the use of a CPT-based N factor of $N_{kt} = 12$. FFP results are given for all three expressions of strain rate normalizations using $\mu = 0.1$ and $\beta = 0.06$ (see also supplementary materials). Overall, a favorable agreement is achieved between FFPs and CPT for all strain rate corrections and both deployments. Significant deviations are restricted to a penetration depth of 0.6–2.0 m. Local seabed inhomogeneities between the FFP and CPT deployments are suspected to explain this deviation. From theory and literature, it is unlikely that such a deviation would be related to the FFP, which theoretically would be expected to be more sensitive to a stiff seabed layer (Steiner et al. 2014).

CPT pore pressure measurements in fine grained soils have also been utilized to estimate the undrained shear strength. While many questions have not been addressed about the application of this procedure to FFP and even less so for FFP u_1 measurements, this data set was used to explore the suggestion to utilize pore pressures to estimate undrained shear strength from FFP. Figure 4 shows s_u derived from the FFP Δu_{1_FFP} data and compared with the CPT estimate of s_u from its cone resistance measurement and from its excess pore pressure, Δu_2 data. Overall, a good agreement is achieved between the estimates of s_u from excess pore pressure measured by the CPT and the FFP, considering $\Delta u_{1\_FFP} \approx \Delta u_2$ derived from Fig. 2. The estimates also suggest a general agreement with s_u derived from CPT q_{net}. Increasing $N_{\Delta u\_FFP}$ to the range 7–9 improves the agreement. The reader is reminded that this study was limited to deepwater clay described in Section 2. Future studies including other and (or) a wider range of soil types may suggest the development of an $N_{\Delta u\_FFP}$ algorithm.

Figure 5 shows the application of the modified Schneider et al. (2008) SBT chart after Robertson (2016). Both FFP and CPT data suggested soils to fall predominantly in the region and just below the lower line of "clay-like contractive soils with high sensitivity" (CCS) and "clay-like contractive soils" (CC). Overall, the application of the modified Schneider et al. (2008) chart after Robertson (2016) seems promising for FFP with a strain rate normalization applied to cone resistance q_{c_FFP} and considering $\Delta u_{1_{FFP}} \approx \Delta u_2$ for excess pore pressure. The very soft deepwater soils appear to fall onto the fringe of the chart, and may represent a future research direction. Friction ratio based SBT charts were neglected here due to the low sleeve friction measurements.

4. Conclusions

FFP deployments with a conventional piezocone were conducted at an offshore location with deepwater depth (~1500 m) and fine-grained sediments. The presented results support the suitability of FFP for geotechnical site investigation as previously suggested by Randolph et al. (2018), representing a relatively fast and easy deployment method particularly in deepwater conditions. The derived undrained shear strengths and SBT classification agreed well with CPT results apart from a deviation that can likely be accounted to local seabed inhomogeneities. The results suggest that understanding of strain rate effects on sleeve friction measurements as well as relations between u_1 and u_2 may benefit from further investigations for FFP.

Article information

History dates

Received: 14 January 2022
Accepted: 12 May 2022
Accepted manuscript online: 20 May 2022
Version of record online: 1 November 2022

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Author information

Author ORCIDs

Nina Stark https://orcid.org/0000-0001-9484-069X

Author notes

Nina Stark served as an Associate Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by Andy Take.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cgj-2022-0029.

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