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Case study on interpretation of cone penetration tests in sandy soil layers

Étude de cas sur l'interprétation des essais de pénétration au cône dans les couches de sol sableux

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ABSTRACT: Based on cone penetration tests (CPT) data, a number of soil's physical and mechanical parameters can be interpretated, like soil unit weight, etc. Even though various studies have been conducted and methods are proposed, uncertainties still exist and the applicability of each method needs be further clarified. A case study on the interpretation of CPT results is performed which based on the measured data from an offshore site close to Shandong Province, China. This paper focus on sandy soil layers and presents an assessment of CPT data interpretation methods for the derivation of sandy soil's unit weight, effective friction angle and relative density. It shows that Mayne's method proposed in 2016 provides better predictions of soil unit weight; Kulhawy's 1990 method performs well in predicting sandy soil's effective friction angle under low-stress conditions, while Robertson's 1983 method is more suitable for high-stress conditions; Schmertmann's model with Baldi's recommendation is better in predicting soil relative density.

RÉSUMÉ: Sur la base des données des essais de pénétration au cône (CPT), plusieurs paramètres physiques et mécaniques du sol peuvent être interprétés, tels que la masse volumique du sol, etc. Bien que diverses études aient été menées et des méthodes proposées, des incertitudes persistent et l'applicabilité de chaque méthode doit être clarifiée davantage. Une étude de cas sur l'interprétation des résultats du CPT est réalisée sur la base des données mesurées sur un site en mer près de la province du Shandong, en Chine. Cet article se concentre sur les couches de sol sableux et présente une évaluation des méthodes d'interprétation des données du CPT pour la détermination de la masse volumique du sol sableux, de l'angle de frottement effectif et de la densité relative. Les conclusions indiquent que la méthode R3 permet de mieux prédire la masse volumique du sol; FA2 performe bien dans la prédiction de l'angle de frottement effectif du sol dans des conditions de faible contrainte, tandis que FA1 est plus adaptée aux conditions de forte contrainte; DR2 montre une bonne capacité à prédire la densité relative du sol.

Keywords: Cone penetration test (CPT); unit weight; effective friction angle; relative density, sandy soil.

1 INTRODUCTION

Cone penetration tests (CPT) are widely used to characterize site conditions for its handiness, multifunctionality and automatization (Lunne *et al.* 1997), especially for offshore sites. During these tests, cone resistance, sleeve friction and pore water pressure (ASTM D5778) are commonly recorded during the probe's penetration (Mayne 2007). Based on these recorded data, a number of soil's physical and mechanical parameters can be interpretated, like soil behaviour type, soil unit weight, etc. Even though various studies have been conducted and methods are proposed (Robertson 2009), uncertainties still exist and the applicability of each method needs be further clarified. A case study on the interpretation of CPT results is performed which based on the measured data from an offshore site close to Shandong Province, China. In this site, series of in-situ cone penetration tests were conducted and soil samples were retrieved at various depth. From which, physical and mechanical parameters were obtained from laboratory tests on these retrieved soil samples, as well as from the interpretation of CPT results. This paper focus on sandy soil layers and presents an assessment of CPT data interpretation methods for the derivation of sandy soil's unit weight, effective friction angle and relative density. Based on the comparison between values obtained by laboratory tests and those derived from CPT data according to various methods, the reliability and applicability of each method are clarified and the most suitable method for each soil parameter is recommended.

2 CURRENT METHODS

Based series of test data, several studies developed methods to derive soil's unit weight(γ), effective friction angle(ϕ'), as well as the relative density(D_r), which are commonly used. These methods are sumarized in Table 1.

Table 1. Summary of current models.

Parameter	Model	Tests	Model equation	Reference
Unit weight γ	R1	-	$\gamma/\gamma_w=0.27\log(R_f)+0.36\log\left(q_c/\sigma_{atm}\right)+1.236$ Where: R_f = friction ratio = $(f_s/q_t)100\%$, γ_w = unit weight of water in same units as γ, σ_{atm}= atmospheric pressure in same units as q_t.	(Robertson and Cabal 2010)
	R2	215	$\gamma=11.46+0.33\log(z)+3.1\log(f_s)+0.7\log(q_c)$ Where: z (m) = depth, f_s (kPa) = sleeve friction, q_c (kPa) = measured tip resistance.	(Mayne *et al.* 2010)
	R3	-	$\gamma/\gamma_w=\left[1.22+0.15\ln\left(100f_s/\sigma_{atm}\right)+0.01\right]$	(Mayne 2016)
Effective friction angle ϕ'	FA1	5	$\tan\phi'=\frac{1}{2.68}\left[0.29+\log\left(\frac{q_c}{\sigma_{v0}'}\right)\right]$	(Robertson and Campanella 1983)
	FA2	24	$\phi'=17.6+11\log(q_{t1})$ Where: q_{t1} = stress normalized tip resistance: $q_{t1}=(q_t/\sigma_{atm})\cdot(\sigma_{atm}/\sigma_{v0}')^{0.5}$	(Kulhawy and Mayne 1990)
Relative density D_r	DR	-	$D_r=\frac{100}{C_2}\cdot\ln\left(\frac{q_c}{C_0\cdot(\sigma_{v0}')^{C_1}}\right)$ Where: C_0 C_1 and C_2 are empirical coefficients parameters.	(Schmertmann 1978)

Model DR was used to interpret sandy soil's relative density from the CPT experimental data, and a total of 4 sets of model parameters (C_0, C_1 and C_2) were selected. These parameters were derived by analysing on sandy soils retrieved from different sites, and reproduced in Table 2.

Table 2. DR Model parameters.

Model	C_0	C_1	C_2	Reference
DR1	0.157	0.550	2.41	(Baldi and O'Neill 1995)
DR2	0.086	0.530	3.29	
DR3	0.140	0.550	2.90	(Jamiolkowski *et al.* 2003)
DR4	0.175	0.500	3.10	

3 CASE STUDY

3.1 General description

This offshore site is close to Shandong Province, belongs to the Yellow Sea of China. Water depth is about 32 m. Series of in-situ piezocone penetration tests were conducted and soil samples were retrieved at various depth. From which, physical and mechanical parameters were obtained from laboratory tests on these retrieved soil samples (GB/T 50123-2019、GB 50021-2001), as well as from the interpretation of CPT results. Figure 1 presents geotechnical stratigraphic log with USCS classification, the values of fines content and measured cone tip resistance, sleeve friction and porewater pressure on shoulder (u_2).

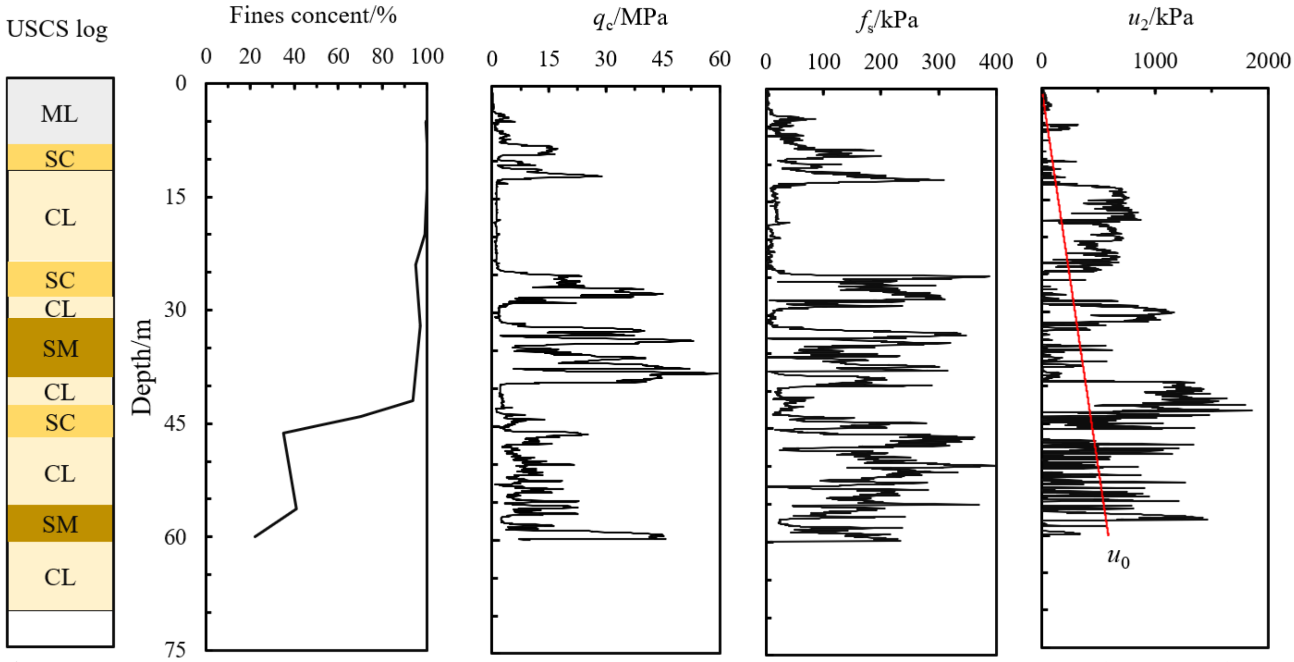

Figure 1. Geotechnical stratigraphic log with USCS classification, fines contents and the recorded CPT data.

3.2 Analysis and discussion

3.2.1 Soil unit weight

Figure 2 (a), (b) and (c) presents a comparison of soil unit weight between measured in lab and derived from CPT data with three methods (R1, R2 and R3) in Table 1. It can be seen that, in general, the relative errors of the three methods are within the range of ±15%, see Figure 2 (d), and they all overestimate the magnitude of soil unit weight, even though there is some underestimation at shallow depth. This overestimation may be caused by the soil disturbance, say stress release when being retrieved at depth below sea bed, which leads to an expansion of soil samples used in laboratory tests. Among these three methods, R3 agrees well with those values from laboratory tests, and R2 shows a poor estimation. Therefore, R3 is recommended to predict the unit weight.

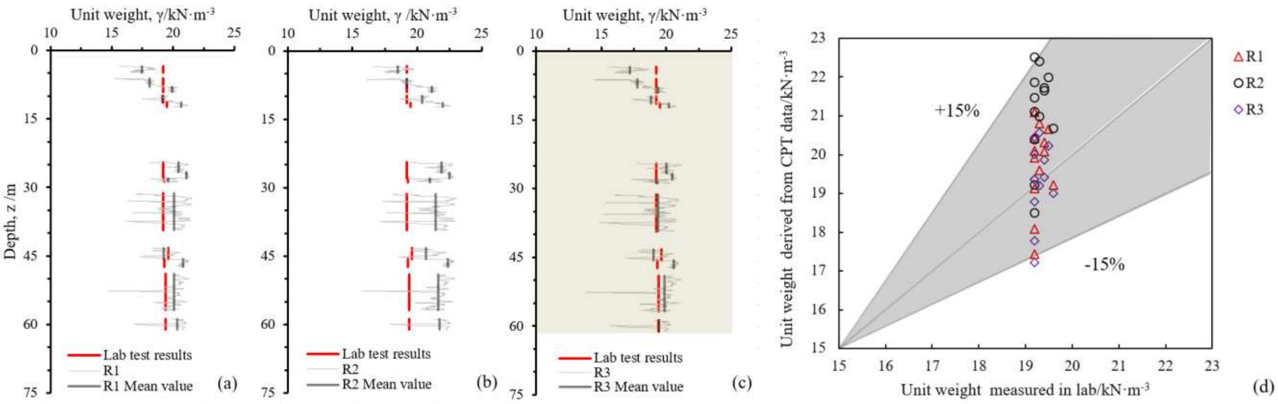

Figure 2. Comparison of soil unit weight between measured in lab and derived from CPT data.

3.2.2 Effective friction angle

Figure 3 (a) and (b) illustrates a comparison of effective friction angle between measured in lab and derived from CPT data with method FA1 and FA2 in Table 1, which shows that FA1 produces an overestimation and FA2 gives an underestimation. So mean values between those calculated with FA1 and FA2 for each layer are plotted in Figure 3 (c). It can be seen that the relative errors of the three methods are generally within the range of ±30%, see Figure 3 (d). In the shallow depth (less than 30m, and corresponding to a lower stress condition), FA2 provides a better prediction, while FA1 gives a very good prediction for the deep depth. The average of the two approaches brings the overall prediction closer to the laboratory test results but fails to produce a better prediction. So, FA2 can be employed at a lower stress condition, while FA1 should be better for higher stress condition.

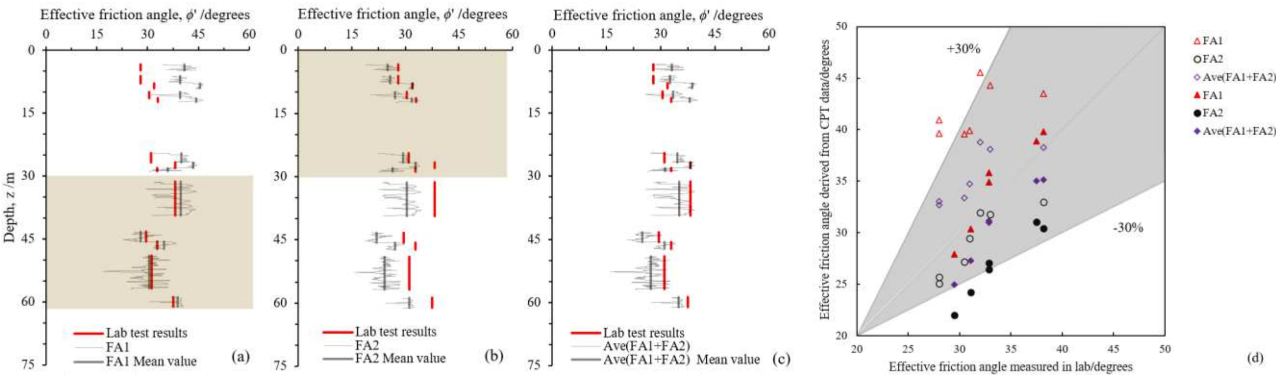

Figure 3. Comparison of soil effective friction angle between measured in lab and derived from CPT data.

3.2.3 Relative density

Figure 4 (a), (b), (c) and (d) shows a comparison of soil relative density between measured in lab and derived from CPT data with four methods (DR1, DR2, DR3 and DR4) in Table 2. It can be seen that, in general, the relative errors of the four methods are within the range of ±40%, see Figure 4 (d), and all these methods underestimate the magnitude of soil relative density, even though there is kind of extremely overestimation at shallow depth. Among these methods, DR2 clearly shows a better estimation, and is recommended to predict sandy soil's relative density.

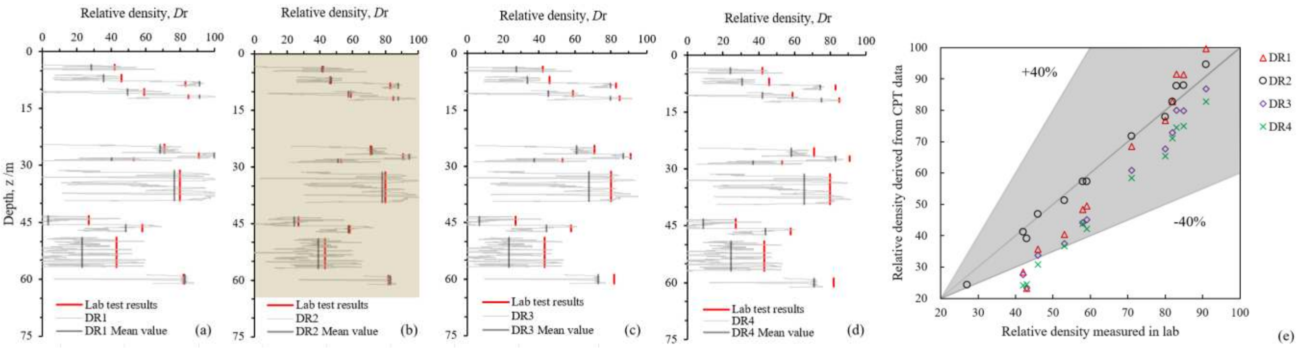

Figure 4. Comparison of soil relative density between measured in lab and derived from CPT data.

4 CONCLUSIONS

Based on a case study focusing on the offshore site in Yellow Sea of China, this paper presents an evaluation on current interpretation methods for CPT data recorded at sandy soil layers. By comparison of soil parameter values between tested in laboratory and interpretated from CPT data, main findings and recommendations are made for sandy soil layers:

Even though a lower estimation is shown in shallow depth, method R3 generally produces a relatively well estimation of soil unit weight. With regards to sandy soil's effective internal friction angle, FA2 produces a better prediction at shallow depth (i.e. lower stress condition) and FA1 suits for deep depth (i.e. higher stress condition). Compared with DR2, the other three methods show relatively poor estimations of sandy soils relative density, therefore DR2 is recommended. This study enables a further design optimization of monopiles used by offshore wind turbine constructed in this site.

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