Evaluating Strength Parameters of Pearl River Offshore Sediments Based on Piezocone Penetration Test

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ABSTRACT: This study investigated the feasibility of evaluating the strength parameters from piezocone penetration test (CPTU) measurements on the basis of a large database for offshore sediments in the Pearl River estuary, China. The peak undrained shear strength, remolded strength, and sensitivity from four types of shear tests were related to CPTU net cone tip resistance, sleeve frictional resistance, and normalized frictional ratio, respectively. Regression analyses were carried out to revisit existing correlations in the literature. The results indicated that the correlations between the three strength parameters and CPTU indices strongly depend on the type of shear test. The cone factor N_{kt} was found to be weakly related to the CPTU excess pore water pressure ratio, and this relationship should also be a function of the type of test. The empirical correlations for the remolded shear strength and sensitivity developed for soft soils may be biased for stiff soils, perhaps due to the impact of lateral stress on the sleeve frictional resistance. Practical recommendations on the adjustment of the empirical correlations were proposed correspondingly.

Keywords: shear strength; piezocone penetration test; sensitivity; offshore sediment

1. Introduction

Strength parameters including the undrained shear strength of undisturbed soils (s_u) and sensitivity (S_t) are the two main considerations in geotechnical design. In offshore projects, a direct measurement of these two parameters from laboratory can be time-consuming and expensive. Therefore, the piezocone penetration test (CPTU) has been widely applied in the marine site characterization due to its fast and cost-saving. The CPTU provides a set of nearly continuous records including the cone tip resistance (q_t), sleeve frictional resistance (f_s) and pore water pressure (u_2). Reasonable correlations for estimating s_u and S_t from these CPTU indices have been proposed in the literature to guide the engineering practice [1-3].

A major limitation of existing correlations is that they depend on many unknown factors such as geologic history, mineral composition, cement and aging [1]. Therefore, these correlations are always recommended to be calibrated according to local experience [1-4].

This study performs a systematic analysis on the evaluation of strength parameters including s_u, S_t and remolded shear strength (s_u^r) from CPTU data, based on a compiled Pearl River offshore sediment database. The empirical coefficients associated with the existing correlations are revisited according to the compiled database. Besides, since the undrained shear strength is a function of boundary conditions and loading stress paths [4], the strength data from different types of shear tests can be quite different, and thus they are analyzed individually in this study. The involved strength tests in the database include the isotropically consolidated triaxial compression for undrained loading (CIUC), unconfined compression (UC) test, unconsolidated undrained (UU) triaxial compression test, and field vane shear test (VST).

2. Strength parameter database for Pearl River estuary marine sediment

The sites under investigation include the Hong Kong-Zhuhai-Macao Bridge (HZMB) site, two Shenzhen projects, one Zhuhai site, one Guangzhou site, and two Macao sites. The locations of these sites are shown in Fig. 1. The numbers of CPTU soundings and boreholes at each site vary over a wide range of 3 to 406, depending on the scales of the testing sites. The HZMB is the largest project that crosses the Pearl River estuary and links Hong Kong, Zhuhai and Macao. The smallest site is a Macao project designed for a tennis court use. Most offshore sediments in the Pearl River estuary at these testing sites are young Quaternary marine and alluvial deposits. Some soils at the Zhuhai and Guangzhou sites are slightly to moderately overconsolidated with the overconsolidation ratios larger than 4.0.

Offshore sediment specimens in the database were collected via a shipborne drilling platform, which allowed the platform and penetration rods to be separated. By using the separable platform, the impact of wave on the interaction between the drilling rod and the platform can be eliminated, and high quality samples can thus be obtained. A stationary piston thin-wall sampler with a diameter of 76 mm or 100 mm was used to collected very soft to soft cohesive soil specimens, whereas a Shelby thin-wall sampler with a diameter of 76 mm was adopted in sampling firm to stiff cohesive soils.

The undrained shear strengths of the cohesive soils were from four types of tests: the isotropically consolidated triaxial compression for undrained loading

(CIUC), unconfined compression (UC) test, the unconsolidated undrained (UU) compression test, and field vane shear test (VST). The data of these tests will be analyzed individually in the following sections.

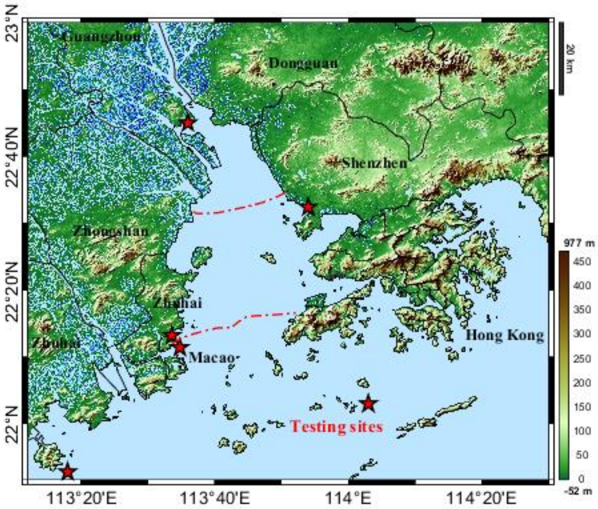

Figure 1. Location of testing sites at the Pearl River estuary

The CPTU soundings were conducted according to the ISSMGE standard [5] with a penetration rate of 2 cm/s and sampling interval of 0.01 – 0.05 m. A Fugro Seacalf system and a Roson system developed by the CCCC-FHDI were used in the marine site investigation. Both systems were performed in the seabed mode. Comparable results were provided by these two pushing systems, and thus they will be analyzed together.

To obtain a representative database for various soil types, the horizontal separating distance between each CPTU sounding and its adjacent borehole is restricted within 5 m. Since soil samples generally have a length of more than 30 cm, the CPTU data points within the corresponding sampling intervals are spatially averaged. The resulting sample volumes of the pariwise CIUC-CPTU, UC-CPTU, UU-CPTU, and VST-CPTU data are 67, 120, 129, and 690, respectively. The size of the VST dataset is the largest among the four datasets, because the vane shear tests were conducted very one meter at each drilling hole. However, it is worth to mention that all VST were performed in very soft to soft soils due to the limitation of the van shear force.

The distribution of CPTU data within the complied database on the Robertson soil classification chart [6] is illustrated in Fig. 2. It is shown that the soil behavior types of the cohesive sediments vary over a wide range of soil zones from sensitive clay to sandy silt. Some slightly to moderately overconsolidated fine-grained soils can have very high normalized cone tip resistance Q_{tn} (e.g., more than 50) when their depths are very shallow. For instance, a measurement of q_t = 0.70 MPa at a depth of 1.5 m produces $Q_{tn} \approx Q_{t1} = (q_t - \sigma_{v0})/\sigma'_{v0}$ = 56 (unit weight = 18 kN/m^3), where σ_{v0} and σ'_{v0} are the vertical total and effective stresses, respectively. Such high Q_{tn} values may lead to the misleading interpretation of the fine-grained soils as coarse-grained soils in the Robertson soil classification chart [6]. Thus, although some CPTU data are classified as sandy soils in Fig. 2, they are still included in the database because they are considered to represent the slightly to moderately overconsolidated fine-grained soils.

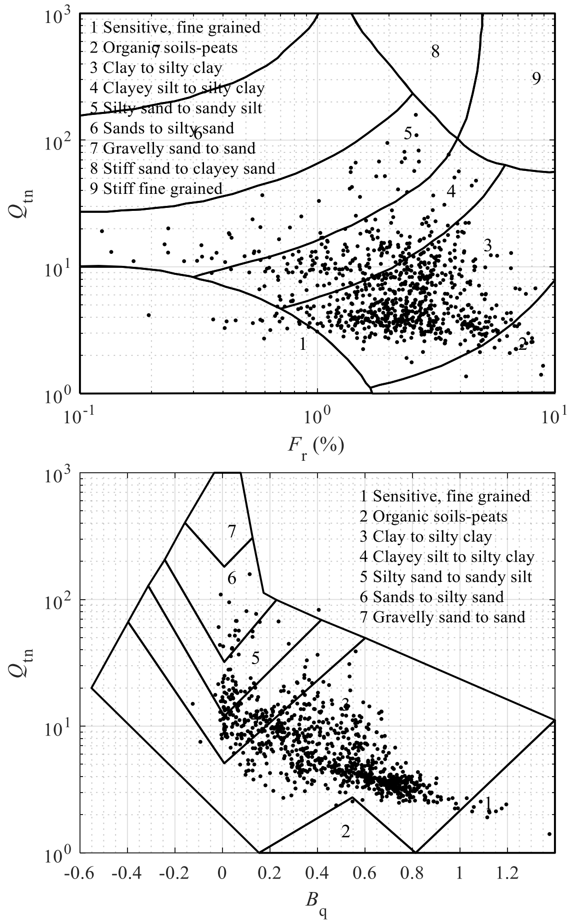

Figure 2. CPTU data of the offshore sediment database on the Robertson soil classification chart

3. Evaluation of undrained shear strength of undisturbed soils

There is a theoretical foundation to establish a correlation between the undrained shear strength (s_u) of an undisturbed soil and CPTU cone tip resistance (q_t) because these two parameters both describe the failure strength of the soil at the in-situ conditions [7]. Most frequently, s_u is related to q_{net} by the following linear function: $s_u = q_{net}/N_{kt}$, where $q_{net} = q_t - \sigma_{v0}$ is the net cone tip resistance, and N_{kt} is the cone factor [8-9]. Although some theoretical solutions for N_{kt} have been proposed in the literature, empirical values are more widely used because they are simple and can be easily adjusted according to site-specific data. Salgado [7] summarized the empirical N_{kt} values for various shear tests and soil types. It was shown that N_{kt} could vary between 7 and 25 [7]. This range is consistent with that recommended by Lunne et al. [7].

Fig. 3 shows the correlations between s_u and q_{net} for the four types of laboratory tests (i.e., CIUC, UC, UU and VST) for the Pearl River offshore sediments. The optimal estimates and 95% confidence intervals (CIs) of N_{kt} obtained using regression method are also shown in Fig. 3. The 95% CI describes the interval in which the true N_{kt} value is 95% likely to be located, and thus a wide 95% CI indicates a high level of uncertainty within the estimate. In Fig. 3, the coefficient of determination (R^2) values are also presented. Favorable s_u-q_{net} correlations with R^2 > 0.80 are developed for the four tests.

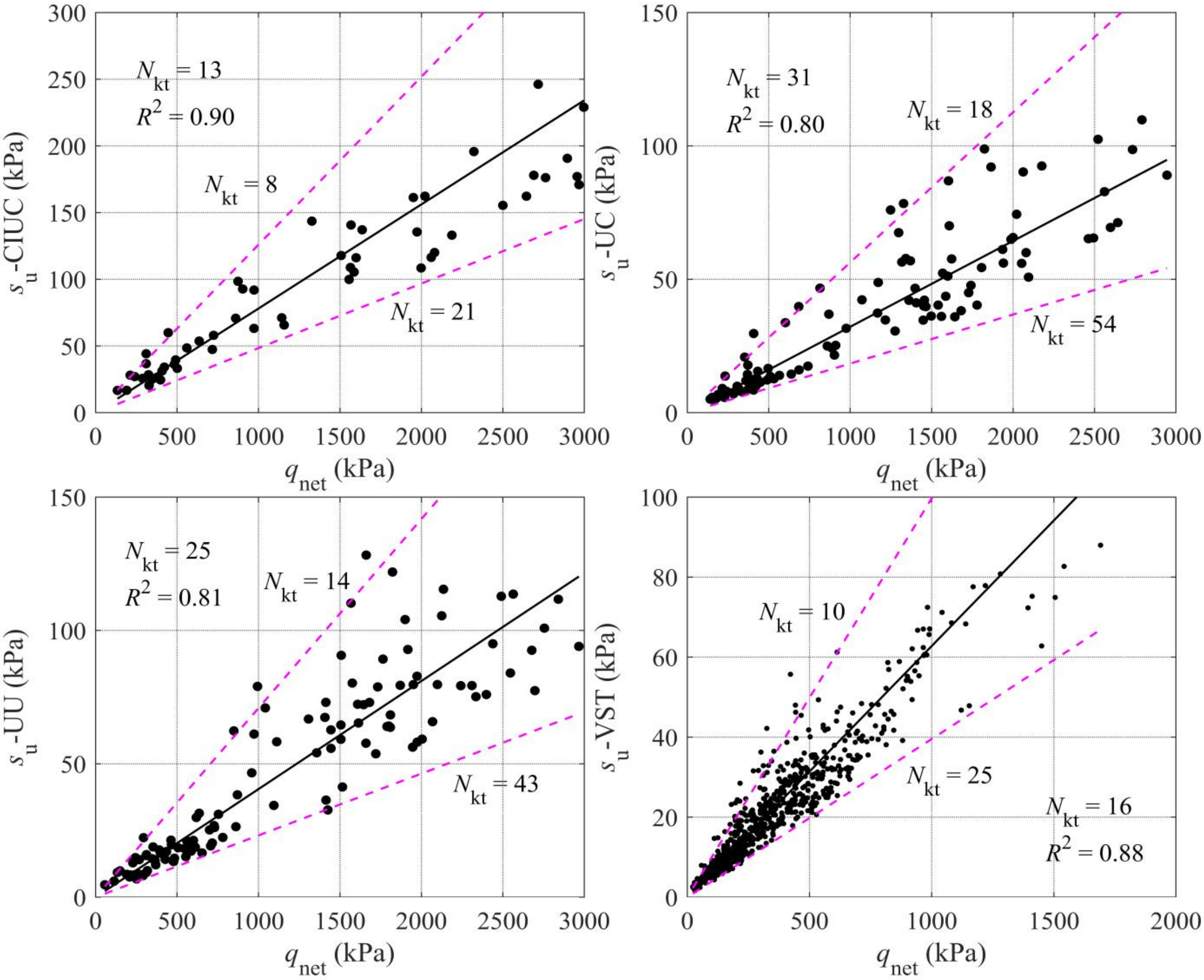

Figure 3. Correlations between s_u and q_{net} for the CIUC, UC, UU and VST tests

It is shown in Fig. 3 that different types of laboratory tests may produce quite different shear strength values. Highest s_u values ranging from 0 to 250 kPa are observed for the CIUC test. Correspondingly, largest N_{kt} values are obtained for this test. The optimal estimate is $N_{kt} = 13$ and 95% CI is 8 to 21 for the CIUC test. The s_u values from the UU test is slightly higher than those from the UC test, and the N_{kt} values also show similar feature. The optimal estimates (95% CIs) of N_{kt} for the UU and UC tests are 25 (14 – 43) and 31 (18 – 54), respectively. The upper limit of s_u values from the VST is the smallest because VST cannot be performed in stiff soils. Nevertheless, their optimal estimate and 95% CI of N_{kt} are within a moderate range of 16 (10 – 25).

The above analysis indicates that only the N_{kt} values for the CIUC and VST are consistent with the empirical range of 7 to 25 reported in the literature [7]. The 95% CIs of N_{kt} for the UU and UC tests in this study are almost two times the empirical range. This implies that the uncertainties within the predicted UU and UC s_u values can be much larger than expected. This is perhaps due to different controlling factors between the UU, UC and CPTU data. The UU test does not allow a reconsolidation before compression, and UC test applies no lateral confining pressure on the soil specimen. Nevertheless, the failure induced by cone penetration occurs with the in-situ confining pressure and may involve some partial consolidation when the silt or sand contents within the surrounding soils are rich [7]. Thus the s_u values from UU and UC tests may be much smaller than expected, and high N_{kt} values are then desired.

Furthermore, it is of interest to investigate the influencing factors of N_{kt} to achieve a better prediction of s_u. Based on either theoretical or experimental solutions, the N_{kt} has been related to many physical or mechanical properties such as the moisture content, plasticity index and rigidity index in the literature [1, 7-9]. To obtain an independent evaluation of s_u from CPTU data, the impact of the excess pore water pressure parameter (B_q) on N_{kt} is considered and the results are shown in Fig. 4. The following exponential function is fitted to the N_{kt}-B_q data for each type of shear tests to produce a linear function in the logN_{kt}-B_q space in Fig. 4:

$$N_{kt} = a\exp\left(bB_q\right) \quad (1)$$

where a and b are empirical coefficients.

The fitted empirical coefficients (a and b) are also presented in Fig. 4. It is shown that distinct negative trends are detected in the N_{kt}-B_q data points for CIUC, UU and VST, although the data scatter around the trends are also evident (R^2 = 0.25-0.42). These trends are consistent with the existing study [3, 8] that N_{kt} may be slightly negatively related to B_q. Nevertheless, this decreasing trend is less significant for the UC test as $R^2 \approx 0$. Therefore, although incorporating B_q may be useful to predict s_u, it is considered important to justify the type of shear test and then empoly different N_{kt}-B_q correlations for different types of tests.

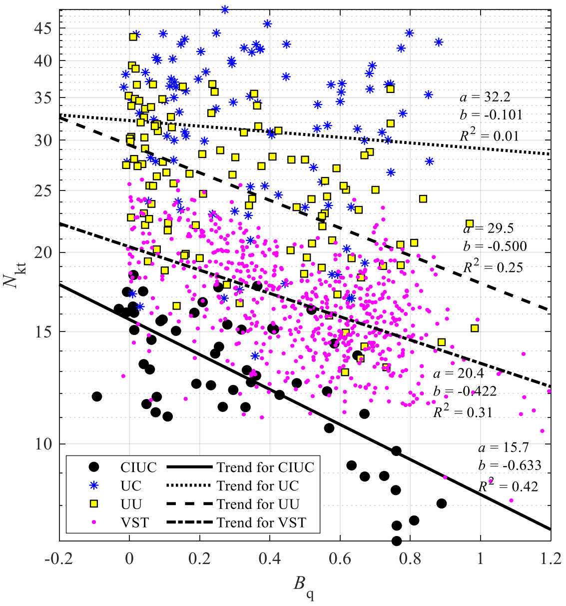

Figure 4. Correlations between N_{kt} and B_q for the four shear tests

4. Evaluation of undrained shear strength of remolded soils

The frictional sleeve adhered after the cone tip evaluates the strength of soils after failure, and thus it can be reasonably related to the remolded shear strength (s_u^r). It has been mentioned in the literature [1-3] that f_s of electric CPTU probe can well approximate s_u^r. The s_u^r–f_s data points in the Pearl River offshore sediment database are shown in Fig. 5. Note that only two types of tests, the UC and VST, provide the s_u^r measurements. According to the trends illustrated in Fig. 5, a simple linear function is selected to model the s_u^r–f_s relationship: $s_u^r = f_s/k$. Using curve fitting approach, the optimal estimates of k are 2.37 for the UC test and 1.12 for the VST test, respectively. The corresponding 95% CIs of k are 0.74–7.63 and 0.35–3.54, respectively. The uncertainty within the empirical coefficient (k) for the UC test is found again larger than that for the VST test.

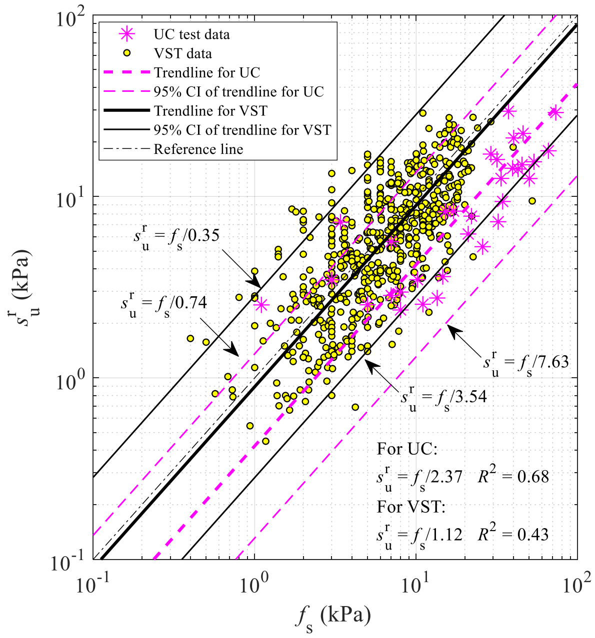

Figure 5. Correlations between s_u^r and f_s for the UC and VST tests

In spite of the evident trend in Fig. 5, the correlations between s_u^r and f_s are not strong, particularly for the VST tests. The R^2 values are 0.68 for the UC test and 0.42 for the VST test, respectively. Therefore, caution shall be taken when replacing s_u^r with f_s during parameter estimation.

A further inspection on Fig. 5 indicates that for stiff soils (e.g., f_s > 20 kPa), f_s tends to be larger than s_u^r as more than 80% data points are below the reference line. This is perhaps due to the fact that in stiff soils, the impact of lateral stress on the frictional sleeve can be significant. Then, f_s is likely to be a combinatorial product of remolded shear strength and lateral stress. Therefore, a large reduction factor shall be applied on f_s to indicate the s_u^r of stiff soils, to eliminate the potential impact of the lateral stress.

5. Evaluation of sensitivity

By estimating s_u from q_{net} and s_u^r from f_s, it is possible to evaluate the sensitivity (S_t) from the CPTU data. By definition, S_t is related to the CPTU normalized frictional ratio $F_r = f_s/q_{net}\times100\%$ by $S_t = N_s/F_r$, where N_s is an empirical coefficient. According to the previously obtained correlations, a rough estimation of N_s is achieved by $N_s = k\times100/N_{kt}$. Using this equation, the apparent optimal estimates of N_s are 7.6 and 7.0 for the UC and VST tests, respectively. These values are very close to the recommended mean values of 7.5 by Lunne et al. [1] and 7.0 by Mayne [2]. Unfortunately, the N_s values obtained above are indeed optimal only when N_{kt} and k are independent, which does not have be the truth.

A more direct estimate of N_s can be achieved from the S_t-F_r data points, as shown in Fig. 6. Moderately strong correlations (R^2 = 0.63 and 0.67) between S_t and F_r were established for the UC and VST tests in Fig. 6. Using the curve-fitting method, the optimal estimates of N_s are 5.6 for the UC test and 6.6 for the VST test. The corresponding 95% CIs are estimated to be 2.8 – 11.4 and 3.1 – 14.0. The optimal estimates are within the empirical range of 5 to 10 recommended by Lunne et al. [1]. However, the estimated 95% CIs in this study are much wider than that in the literature.

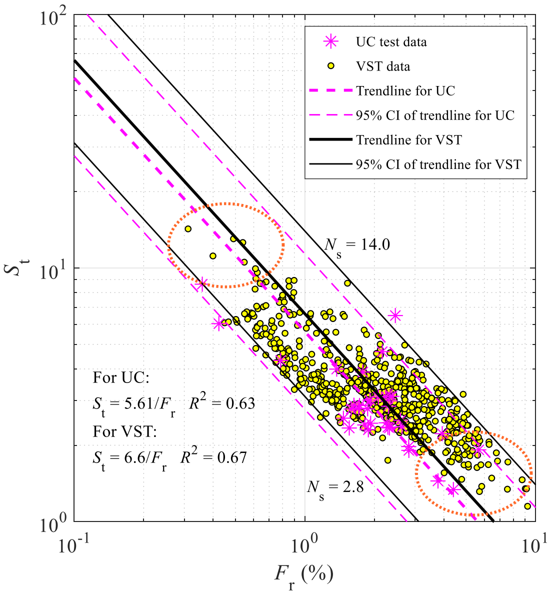

Figure 6. Relationships between S_t and F_r

Besides, the data points in Fig. 6 imply that the above N_s estimates may be suitable only for 0.8% < F_r < 4%, whereas they tend to be biased for very sensitive soils with S_t > 9 (or F_r < 0.8%) and insensitive to slightly sensitive soils with S_t < 2 (or F_r > 4%). This bias is highlighted using the dashed ellipse in Fig. 6. It can be seen that almost all data points are below the optimal trendlines for S_t > 9, and more than 90% data points are above the optimal trendlines for S_t < 2.

The bias in the high sensitivity region is not well understood. There is also a chance that it is because the sample size in this region is too limited, i.e., less than ten. However, the bias in the high F_r (F_r > 4%) region is less likely due to the limitation of sample size, which is 93 for the VST dataset. This bias can be related to the overestimation of s_u^r from f_s for stiff soils, as discussed in the previous section. This overestimation in turn leads to the underestimation of S_t using the function of $S_t = N_s/F_r$. Since stiff cohesive soils are generally associated with high F_r values, it is not surprising that the estimation of S_t from F_r can be highly biased when F_r > 4%. Therefore, a large value of N_s shall be recommended for these stiff soils.

6. Conclusions

This study performed a systematic investigation on the evaluation of strength parameters including the undrained shear strength of undisturbed soils (s_u), remolded shear strength (s_u^r) and sensitivity (S_t) from the piezocone penetration test (CPTU) indices for the Pearl River offshore sediments. The types of shear tests compiled in this study included the CIUC, UC, UU tests and the VST. Correlations for predicting s_u from q_{net}, s_u^r from f_s, and S_t from F_r were fully analyzed and discussed. It was shown that the cone factor N_{kt} strongly depends on the type of shear test. Weak correlations between N_{kt} and CPTU excess pore water pressure ratio (B_q) as a function of test type were also observed. Weak to moderately strong s_u^r–f_s and S_t–F_r correlations were also established for the UC and VST data. These two correlations were deemed suitable for soft soils, but they may be biased for stiff soils with f_s > 20 kPa or F_r > 4%. Practical recommendations on the selection of empirical coefficients embedded in the correlations were proposed.

Acknowledgements

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