CPTU Interpretation for Silty Sand in Binh Dai Offshore Wind Farm

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Abstract. Geotechnical engineering parameters are of significant effect on foundation design. In-situ tests such as piezocone penetration test (CPTU) are widely used to estimate of effective internal friction angle of sand. How to choose appropriate interpretation method for CPTU is a big problem for geotechnical design. As a case study, the laboratory test results and CPTU results of two Phases (Phase 2 and Phase 3) in Binh Dai offshore wind farm of Vietnam were analysed to establish the correlation between effective internal friction angle φ’ and corrected tip resistance qt. The effective internal friction angles of the four sand layers in Binh Dai are found to be linear dependent on the soil depth. Meanwhile, linear expressions between effective internal friction angle φ’ and corrected tip resistance qt are proposed, which have high quality in prediction of effective internal friction angle φ’ for silty sand in Binh Dai. It worth noting that direct use of CPTU method established by other site’s data without any site specific experience would lead to misestimate at offshore wind farm in Vietnam. New correlations should be established by using site specific data cautiously.

1. Introduction
Geotechnical engineering parameters are of significant effect on foundation design. Sand layer is widely distributed in offshore area in Vietnam. It is clearly that sand is non-cohesive soil and granular material, which would be easily fallen apart after borehole sampling. Considering that it is hard to obtain undisturbed sand samples, in-situ tests such as piezocone penetration test (CPTU) are widely used to obtain the strength parameter of sand [1]. It worth noting that CPTU can only get the tip resistance qc, sleeve friction fs, and pore pressure u2, which means that interpretation process is needed both for CPTU. Hence, how to accurately interpret the strength parameter of sand becomes a problem [2]. The interpretation method would be site specific, where the interpretation parameter would be different at different sites [3]. In this paper, the direct shear test (DS), and triaxial consolidated drained shear test (CD) are carried out at phase 2&3 of Binh Dai offshore wind farm in the coast area of Vietnam. Expressions with high quality in SPT and CPTU interpretation of internal friction angle for sand are established, which can be used for offshore wind farms at Vietnam in the future.
2. Site Condition

2.1. Project Overview

Binh Dai offshore wind farm (Figure 1) is located at Thua Duc Commune, Binh Dai District, Ben Tre Province, Vietnam. The whole project with a total capacity of 310 MW had been divided into 8 phases, 24 wind turbines are included in Phase 2 and Phase 3, with 12 wind turbines per each. The distances from Phase 2 and Phase 3 to shore are about 2.5 km and 4.5km, respectively. The water depth ranges from approximately 3m to 9m below mean sea level (MSL) in Phase 2 and 3m to 5m MSL in Phase 3.

![Location of Binh Dai offshore wind farm in Vietnam](a) Phase 2 (a) Phase 3

Figure 1. Location of Binh Dai offshore wind farm in Vietnam.

2.2. Soil Conditions

Table 1. Soil conditions in Phase 2 and Phase 3 of Binh Dai offshore wind farm.

| No. | Soil type                                      | Phase 2 | Phase 3 |
|-----|------------------------------------------------|---------|---------|
|     |                                               | Top [m] | Bottom [m] | Thickness [m] | Top [m] | Bottom [m] | Thickness [m] |
| 1   | Silty sand, loose to medium dense              | 0       | 0.7~7.2  | 0.7~7.2       | 0       | 0.4~10.4  | 0.4~10.4       |
| Layer 2 | Organic clay, very soft to soft             | 0.7~7.2 | 11.9~18.1 | 5.3~16.3      | 0.4~10.4 | 13.0~16.0 | 3.2~13.8       |
| Layer 2a | Silty sand, loose to medium dense            | 4.1~5.0 | 6.3~8.3  | 2.2~3.3       | 3.5~5.5  | 6.8~6.9   | 1.3~3.4       |
| Layer 3b | Sandy clay, stiff                           | /       | /        | /             | 15.4~16.0 | 16.0~19.5 | 0.6~4.0       |
| Layer 3 | Silty sand/clayey sand, loose to medium dense | 11.9~16.7 | 16.0~17.8 | 1.1~4.1       | 13.6~16.0 | 17.8~26.2 | 4.2~10.0       |
| Lense 3a | Sandy clay, very stiff                      | /       | /        | /             | 18.8     | 22.0      | 3.2           |
| Layer 4 | Clay with sand, stiff to very stiff          | 12.0~18.1 | 22.4~48.4 | 6.6~33.5      | 14.05~26.6 | 19.7~50.9 | 4.0~26.9       |
| Lense 4a | Silty sand/clayey sand, medium dense        | 20.8~22.2 | 22.7~24.8 | 1.9~2.6       | 16.4~20.0 | 18.2~22.8 | 1.8~4.5       |
| Layer 5 | Silty sand/clayey sand, medium dense to dense | 22.4~48.4 | 32.1~56.0 | 5.6~29.6      | 19.7~50.9 | 40.0~60.0 | 7.1~37.0       |
| Lense 5a | Clay, very stiff to hard                    | 38.3~44.8 | 44.0~46.0 | 1.2~5.7       | 29.5~34.7 | 32.8~37.0 | 2.3~3.3       |
| Layer 6 | Clay, very stiff to hard                    | 32.1~55.0 | 50.0~64.0 | 3.4~27.9      | 39.1~58.2 | 42.3~68.2 | 3.2~11.5       |
| Layer 7 | Silty sand, very dense                      | 38.0~64.0 | 62.3~70.0 | 6.0~32.0      | 40.0~68.2 | 70.0(end) | 1.8~30.0       |
| Layer 8 | Clay, very stiff                            | 62.3~68.3 | 70.0(end) | 1.7~7.7       | /        | /        | /             |
Borehole and CPTU were carried in each wind turbine location. All boreholes were drilled to 70m deep, undisturbed soil sample (clayey soil) and disturbed soil sample (sandy soil) are collected with an interval of 2m. All of samples were stored and transported in accordance with the requirements of ASTM D4220. SPT is carried out according to the requirements of ASTM D1586, with an interval of 2.0m in all the boreholes. Sandy soil samples were taken by SPT sampler tube or single core sampler tube (for coarse sand samples or samples with a lot of gravel, the sample shall be taken from the SPT sampler and shall be protected by plastic bags and PVC pipes immediately after taking samples from the borehole). The samples were immediately transferred to the laboratory after completion of each borehole. The soil conditions in Phase 2 and Phase 3 are shown in table 1.

The penetration depth of CPTUs ranges to 50.0 m below the seabed. The CPTU refusal occurred in dense to very dense sand layer or gravel layer (which might cause damage on the probe) around 28m to 50m in part of wind turbine locations, when the tip resistance \( q_c \) might exceed 60MPa. The drilling machine can be used to clear the hole and continue penetration.

The soil conditions for top to the bottom of 70m (end of borehole) are presented in table 1. Eight main layers with four sand layers (Layer 1, 3, 5, 7), four clay layers (Layer 2, 4, 6, 8) and five interbedded layers (Lense 2a, 3a, 3b, 4a, 5a) are found in Binh Dai offshore wind farm. In this research, the four main sand layers are taken as the object.

2.3. Properties of Sand Layers

![Grain size distribution of the four sand layer in Binh Dai offshore wind farm.](image)

Sieve analysis, hydrometer analysis and physical properties tests are carried out for the sandy layers according to the relevant ASTM standards. Figure 2 presents the grain size distribution curve of the four main sand layers in Phase 2 and Phase 3. As shown in figure 2, the grain size distribution curves of Layer 1, Layer 3 and Layer 5 are found to be quite similar to each other, where Layer 7 is coarser than the other three sand layers. The physical properties of the four main layers are summarized in table 2. The median diameter \( D_{50} \) of the four layers (Layer 1, 3, 5, 7) increases with the growing soil depth, with 0.099mm, 0.104mm, 0.146mm, 0.341mm in Phase 2, and 0.099mm, 0.111mm, 0.130mm and 0.171mm, respectively. Due to the self-weight stress increasing with the soil depth, the sand layers become denser, where the initial void ratio decreases and density increases.
Table 2. Physical properties of sand layers in Binh Dai offshore wind farm.

| Layer   | Grained size distribution | Physical properties |
|---------|---------------------------|---------------------|
|         | Phase 2                   |                     |
|         | Gravel (%) | Sand (%) | Silt (%) | Clay (%) | D_{50} (mm) | w (%) | o_{0} (%) | $\rho$ (g/cm$^3$) | $G_s$ | $C_u$ | $C_c$ |
| Layer 1 | 0.0                      | 64.0               | 26.1     | 9.9      | 0.099       | 26.7  | 0.772     | 1.901           | 2.658 | 15.1  | 4.0   |
| Layer 3 | 0.3                      | 64.8               | 18.0     | 16.9     | 0.104       | 22.6  | 0.658     | 1.968           | 2.661 | 14.3  | 2.4   |
| Layer 5 | 0.1                      | 68.0               | 22.0     | 9.9      | 0.146       | 23.3  | 0.663     | 1.974           | 2.662 | 17.2  | 2.9   |
| Layer 7 | 1.7                      | 76.8               | 14.9     | 6.6      | 0.341       | 18.0  | 0.536     | 2.044           | 2.661 | 11.3  | 2.0   |
|         | Phase 3                   |                     |
|         | Gravel (%) | Sand (%) | Silt (%) | Clay (%) | D_{50} (mm) | w (%) | o_{0} (%) | $\rho$ (g/cm$^3$) | $G_s$ | $C_u$ | $C_c$ |
| Layer 1 | 0.0                      | 63.7               | 25.9     | 10.4     | 0.099       | 27.0  | 0.779     | 1.900           | 2.661 | 12.2  | 2.9   |
| Layer 3 | 0.4                      | 63.9               | 20.1     | 15.6     | 0.111       | 24.7  | 0.701     | 1.955           | 2.667 | 20.1  | 3.0   |
| Layer 5 | 0.5                      | 69.3               | 18.6     | 11.6     | 0.130       | 21.2  | 0.614     | 2.000           | 2.663 | 14.9  | 2.9   |
| Layer 7 | 0.7                      | 78.1               | 12.9     | 8.3      | 0.171       | 19.2  | 0.562     | 2.034           | 2.664 | 9.9   | 2.0   |

3. Strength Properties of Sand

3.1. Laboratory Testing

![Figure 3](image-url)
Direct shear test (DS) were carried out in accordance with the requirements of ASTM D3080 for determining the internal friction angle $\phi$ of sand samples, of which the shearing rate 0.02mm/min. Three level of vertical pressures were selected for each set of sand samples as follows: 1) 50kPa, 100kPa, 200kPa for sand samples at 0 to 20m; 2) 100kPa, 200kPa, 400kPa for sand samples at 20m to 40m; 3) 200kPa, 400kPa, 800kPa for sand samples at 40m to 80m.

Triaxial consolidated drained shear test (CD) were performed to determine the relationship between stress and strain and mechanical parameters of cylinder specimen by triaxial cell. The specification of sand cylinder specimen is 38mm in diameter and 80mm in height. The three stress levels of specimens in same set of sand samples are same with that of direct shear test.

Figure 3 plotted the internal friction angle $\phi$ of the four main sand layers in both Phase 2 and Phase 3. It could be clearly seen that the internal friction angle results of Layer 1 are the lowest, and the internal friction angle results of Layer 7 are the highest. As presented in figure 3, the internal friction angles of DS test and CD test in Binh Dai offshore wind farm seems to be linearly dependent on the soil depth. After linear fitting, the following regression expressions with good quality are obtained:

$$\phi' = 22.33 + 0.253 z, \quad R^2 = 0.7664$$ \hspace{1cm} (Phase 2, DS) \hspace{1cm} (1)

$$\phi' = 24.51 + 0.253 z, \quad R^2 = 0.7957$$ \hspace{1cm} (Phase 3, DS) \hspace{1cm} (2)

$$\phi' = 24.89 + 0.254 z, \quad R^2 = 0.8114$$ \hspace{1cm} (Phase 2, CD) \hspace{1cm} (3)

$$\phi' = 26.01 + 0.246 z, \quad R^2 = 0.7539$$ \hspace{1cm} (Phase 3, CD) \hspace{1cm} (4)

where $\phi'$ is the effective internal friction angle of sand, $z$ is the soil depth. Based on the linear fitting formulae, the intercepts of CD test results are slightly higher than that of the DS test results. However, the slopes of the four formulae are quite similar, which are 0.253, 0.253, 0.254 and 0.246, respectively.

3.2. Piezocone Penetration Test

Piezocone penetration test (CPTU) is one of the most popular in-situ tests to evaluate the strength parameter of sand, with measured data of tip resistance $q_t$, sleeve friction $f_s$ and pore pressure $u_z$. The corrected cone resistance $q_i$ considering pore water effects would be the most important parameter to interpret internal friction angle $\phi$ for quartz sands based on the calibration chamber test results. Robertson and Campanella [5] had proposed a correlation to estimate the internal friction angle $\phi'$ for quartz sands based on the calibration chamber test results.

$$\tan \phi' = \frac{1}{2.68} \log \left( \frac{q_i}{\sigma_{vo}} \right) + 0.29$$ \hspace{1cm} (6)

where $\sigma_{vo}$ is the vertical effective stress at the same depth with the measured $q_i$ data. Kulhawy and Mayne [6] suggested a relationship for quartz sand by using high quality field testing data:

$$\phi' = 17.6 + 11 \cdot \log (Q_m)$$ \hspace{1cm} (7)

$$Q_m = \left( \frac{q_i - \sigma_{vo}}{P_s} \right) \left( \frac{P_s}{\sigma_{vo}} \right)^n$$ \hspace{1cm} (8)

where $\sigma_{vo}$ is the vertical total stress at the same depth with the measured $q_i$ data, $P_s$ is the atmospheric pressure, $n$ is the empirical coefficient, which can be selected as 1.0. It worth noting that the above internal friction angle CPTU interpretation methods are based on the data of quartz clean sands, which may not be suitable for the silty sand in Vietnam offshore area. New CPTU interpretation method or correlation between internal friction angle $\phi'$ and CPTU data should be established with site specific available data in Vietnam. Based on the on hand DS and CD test results in Binh Dai offshore wind farm, we can establish the correlation between the $q_i$ data and effective internal friction angle $\phi'$. The relevant
and effective internal friction angle \( \phi' \) data are plotted in figure 4. Figure 4a and figure 4b provide the separate data of Phase 2 and Phase 3, which show fair good linear relationships.

\[
\phi' = 25.63 + 0.256q_t, \quad R^2 = 0.4394 \quad \text{(Phase 2, DS)}
\]  
\[
\phi' = 29.02 + 0.198q_t, \quad R^2 = 0.4114 \quad \text{(Phase 2, CD)}
\]  
\[
\phi' = 26.73 + 0.303q_t, \quad R^2 = 0.5747 \quad \text{(Phase 3, DS)}
\]  
\[
\phi' = 28.06 + 0.276q_t, \quad R^2 = 0.5412 \quad \text{(Phase 3, CD)}
\]  

Figure 4c present the integrated data of Phase 2 and Phase 3, the calibrated expressions of DS and CD test results are as follows:

\[
\phi' = 26.37 + 0.268q_t, \quad R^2 = 0.4781 \quad \text{(Phase 2&3, DS)}
\]  
\[
\phi' = 28.35 + 0.242q_t, \quad R^2 = 0.4898 \quad \text{(Phase 2&3, CD)}
\]  

Figure 4. Correlation between internal friction angle \( \phi' \) and corrected tip resistance \( q_t \).

### 3.3. Preliminary Application of Proposed CPTU Interpretation Methods

In order to verify the applicability of the proposed equation (13) and (14), the CPTU data and laboratory test results of WT 206 location in Phase 2 and WT 306 location in Phase 3 are adopted to do the analysis. Both the methods proposed by Robertson and Campanella [5] and Kulhawy and Mayne [6] are adopted for comparison. The CPTU interpretation results of WT 206 and WT 306 are presented in figure 5a and
figure 5b, respectively. At the top sand layer (Layer 1) from 0m to 8m, the interpretation results of Robertson and Campanella [5] and Kulhawy and Mayne [6] are extremely higher than the measured data, with an overestimation of 100%. In addition, these two kind of method would also overestimate the internal friction angle of the other sand layers below. It would be very critical for the foundation design, if the strengths of sand layers are overestimated. The method proposed in this paper show better interpretations than the two previously proposed methods for both WT 206 and WT 306. The deviations could be that the previous proposed methods are based on the data of clean quartz sand, but the proposed expressions in this paper is based on the data of silty sand. The internal friction angle of silty sand would be lower than that of clean quartz sand. Considering that the silty sand layers are mainly distributed at offshore area in Vietnam, it could be better to use the expressions proposed in this paper, rather than directly used the methods proposed by Robertson and Campanella [5] and Kulhawy and Mayne [6] without any site experience.

![CPTU interpretation of internal friction angle in Binh Dai offshore wind farm.](image)

**Figure 5.** CPTU interpretation of internal friction angle in Binh Dai offshore wind farm.

4. Conclusions
As a case study, the laboratory test and in-situ test results of Binh Dai offshore wind farm in Vietnam are analysed. The effective internal friction angles of the four sand layers are found to be linear dependent on the soil depth. Based on direct shear test and triaxial consolidated drained shear test results, new correlation expressions between the measured CPTU data and laboratory test results are established. After application of the new proposed expressions and previously proposed method by Robertson and
Campanella [5] and Kulhawy and Mayne [6], the proposed two expressions \( \varphi' = 26.37 + 0.268q_t \) and \( \varphi' = 28.35 + 0.242q_t \) have good quality for internal friction angle CPTU interpretation in Vietnam. In addition, it is also found that these two kinds of method would overestimate the internal friction angle of silty sand at offshore wind farm in Vietnam, directly use of these two methods without any site experience would cause harmful consequence in foundation design. New correlations should be established use site specific data cautiously.

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