Strength assessment of Tra Vinh clay for offshore wind power project in Vietnam

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Abstract. Sample disturbances in offshore wind power projects are inevitable and much higher than onshore projects. Unconsolidated undrained shear tests (UU) results could underestimate the in-situ strength of clay, which would lead to a huge waste in foundation design. Piezocone penetration test (CPTU) can interpret precise soil strength for in-situ soil if appropriate interpretation parameters are chosen. As a case study, laboratory tests and CPTU results of Tra Vinh offshore wind power projects in south Vietnam are analysed to acquire accurate soil strength. SHANSEP (Stress history and normalised soils engineering properties) method are adopted to minimize the sample disturbances. Linear correlations between strength and depth are discovered for Tra Vinh organic clay and Tra Vinh clay. The normalised undrained shear strength \(\frac{s_u}{\sigma_d} \) for Tra Vinh organic clay at 0m to 20m and Tra Vinh clay at 20m to 80m are approximately 0.17 and 0.34 obtained from DSq test, where \(\frac{s_u}{\sigma_d} \) of CU test are relatively higher. The normalised undrained shear strength \(\frac{s_u}{\sigma_d} \) is found to be negatively linear correlated with liquidity index. SHANSEP and OCR-to-CPTU interpretation by using the conservative \(\frac{s_u}{\sigma_d} \) value from DSq test is in good agreement with laboratory test results of Tra Vinh organic clay at 0m to 20m, and reappears the in-situ undrained shear strength of Tra Vinh clay from 20m to 70m. After calibration by taking the interpretation results of SHANSEP and OCR-to-CPTU method as a reference, \(N_k \) values of 25 and 17 are respectively recommended for Tra Vinh organic clay and Tra Vinh clay in the offshore area, which is more convenient for CPTU interpretation in engineering projects.

Key words: Tra Vinh Clay, Offshore wind power projects, CPTU, SHANSEP, normalised undrained shear strength

1. Introduction
Geotechnical engineering parameters of clayey soil play a curial part in foundation design [1]. Sample disturbance of borehole drilling and transportation [2-5] could result in an underestimate of undrained shear strength of laboratory tests, especially for the unconsolidated triaxial undrained shear test (UU) and unconfined compression test (Qu). Adopting UU and Qu test results for foundation design would lead to a huge waste. Hence, undrained shear strength evaluation of clay becomes a serious problem in offshore wind power projects. Theoretical methods, such as Modified Cam Clay model [6] and other models [7,8] had already been used in undrained shear strength evaluation by establishing normalised undrained shear strength \(\frac{s_u}{\sigma_d} \) of normally consolidated clay and OCR. However, the OCR value
cannot be precisely obtained by oedometer test of disturbed samples. Theoretical method is difficult and inconvenient to evaluate undrained shear strength of in-situ clay. Previous researches [9,10] had using consolidated direct quick shear test (DSq) and consolidated triaxial undrained shear test (CU) to evaluate the soil strength, some experience correlation between the physical properties (such as liquidity index) and undrained shear strength had also been proposed [11,12]. As a case study, laboratory tests and CPTU results of Tra Vinh offshore wind power projects in Vietnam have been analysed to interpret undrained shear strength of Tra Vinh organic clay and clay. The recommended normalised undrained shear strengths $s_u/\sigma_0'$, and CPTU interpretation parameters $N_{k1}$ of Tra Vinh organic clay and Tra Vinh clay have also been provided, which can be used for strength assessment for projects in Tra Vinh.

2. Physical properties of Tra Vinh clay

2.1. Site overview

Tra Vinh V1-2 offshore wind power project is located in Hiep Thanh Commune, Duyen Hai Town, Tra Vinh Province, Vietnam (Figure 1). The designed capacity is 48MW in total, with 12 wind turbines.

![Figure 1. Location of Tra Vinh V1-2 offshore wind power project in Vietnam](image)

2.2. Soil conditions

Each CPTU with 70m depth is carried out at each wind turbine location. One-fourth of the 12 wind turbine locations, namely 3 wind turbine locations are selected to drill the boreholes with a depth of 80m. Thin-walled tube sampler with a diameter of 76mm is used to take clayey soil samples according to ASTM D1587, with an interval of 2m. Unified Soil Classification System (USCS) is adopted to classify the soil type according to ASTM D2487.

Overview of soil strata in Tra Vinh V1-2 offshore wind power project is listed in Table 1. Three clayey soil layers are discovered, where Layer 2 is soft organic clay, Layer 3 and Layer 5 are stiff clay. At the top, a very thin silty sand layer of less than 2m is discovered, and interbedded sand layers Layer 2a, Layer 3a and Layer 5a are also discovered in Layer 2, Layer 3 and Layer 5, respectively.

| No. | Soil type          | Top [m] | Bottom [m] |
|-----|--------------------|---------|------------|
|     |                    |         |            |
Layer 1 Silty sand, loose to medium dense 0 0.6~2.2
Layer 2 Organic clay, very soft 0.6~2.2 18.0~19.8
Layer 2a Silty sand, loose to medium dense 4.0~5.0 8.0~10.0
Layer 3 Clay, Stiff to very stiff 18.0~19.8 40.0~44.9
Layer 3a Silty sand, medium dense 22.5 28.0
Layer 4 Silty sand, medium dense to dense 40.0~44.9 44.0~54.0
Layer 5 Clay, Stiff to very stiff 44.0~54.0 56.5~80.0
Layer 5a Silty sand, dense 56.6 58.0
Layer 6 Silty sand, dense 56.0~76.5 80.0 (finished)

2.3. Physical properties

Figure 2 shows the plasticity chart of clayey soil in Tra Vinh V1-2. Layer 2 is classified as OL (Low plasticity organic clay) and OH (High plasticity organic clay). Layer 3 and Layer 5 are classified as CL (Low plasticity clay) and CH (High plasticity clay).

![Figure 2. Casagrande plasticity chart for clayey soil in Tra Vinh](image)

The physical properties of the three layers are summarised in Table 2.

| Layer | Grained size distribution | Physical properties |
|-------|---------------------------|---------------------|
|       | Sand (%) | Silt (%) | Clay (%) | $w_L$ (%) | $I_p$ (%) | $I_L$ (%) | $w$ (%) | $e_0$ | $\rho$ (g/cm³) | $G_s$ |
| Layer 2 | 5.0 | 45.6 | 49.4 | 52.4 | 28.3 | 1.07 | 54.4 | 1.522 | 1.628 | 2.658 |
| Layer 3 | 18.4 | 44.1 | 37.5 | 45.3 | 23.1 | 0.30 | 29.1 | 0.832 | 1.902 | 2.699 |
| Layer 5 | 16.4 | 48.8 | 34.8 | 29.4 | 22.3 | 0.30 | 29.4 | 0.845 | 1.895 | 2.701 |

3. Undrained shear strength evaluation

3.1. Sample quality evaluation
Considering that clayey soil samples are easily disturbed during drilling and transportation, and the mechanical parameters are strongly dependent on the sample quality. To evaluate the sample quality, the pore volume relative to the initial pore volume $\Delta e/e_0$ [3] had been adopted to qualify the sample disturbance. $\Delta e/e_0$ of all the 81 clayey soil samples are presented in Figure 3. 4 samples and 20 samples are in Level 1 and Level 2 range, respectively. Over 69% of the samples are in the poor quality range of Level 3. 1 sample is severely disturbed, which is in Level 4 range.

**Table 3. $\Delta e/e_0$ criteria for sample disturbance evaluation**

| OCR | $\Delta e/e_0$ criteria | $\Delta e/e_0$ range |
|-----|--------------------------|----------------------|
| 1~2 | Very good to excellent (1) | $<0.04$              |
|     | Good to fair (2)          | 0.04–0.07            |
|     | Poor (3)                  | 0.07–0.14            |
|     | Very poor (4)             | $>0.14$              |
| 2~4 | Very good to excellent (1) | $<0.03$              |
|     | Good to fair (2)          | 0.03–0.05            |
|     | Poor (3)                  | 0.05–0.10            |
|     | Very poor (4)             | $>0.10$              |

**Figure 3. Sample disturbance evaluation for Tra Vinh clay**

3.2. Undrained shear strength from Laboratory tests

Four types of mechanical laboratory tests, direct quick shear test (DSq), triaxial unconsolidated undrained shear test (UU), triaxial consolidated undrained shear test (CU) and unconfined compression test (Qu) are carried to obtain the undrained shear strength of clayey soil. The laboratory test results of organic clay (Layer 2) and clay (Layer 3&5) are provided in Figure 4. It seems possible that the undrained shear strength obtained from DSq, UU and CU tests are linear dependent on soil depth, both for Layer 2 (OH or OL) and Layer 3&5 (CH or CL). But for the unconfined compression test (Qu), no significant linear correlations are found between undrained shear strength and soil depth, which might attribute to the sample disturbance.

For Clay of Layer 3 and Layer 5, results of DSq and CU test are higher than the results of UU and Qu tests. The reason might be that DSq test and CU test have a consolidation process before shearing, where reconsolidation will reduce the adverse effect of sample disturbance. The linear expressions for Tra Vinh organic clay (OH/OL) and clay (CH/CL) are as follows:

$$s_u,DSq = 3.582 + 0.979z , R^2=0.5296 \quad \text{(Layer 2, soft organic clay)}$$  (1)
\[ s_{u,\text{UU}} = 14.093 + 0.471z, \quad R^2=0.8724 \quad \text{(Layer 2, soft organic clay)} \]  
\[ s_{u,\text{CU}} = 18.472 + 1.507z, \quad R^2=0.9359 \quad \text{(Layer 2, soft organic clay)} \]  
\[ s_{u,\text{DSq}} = 12.372 + 2.718z, \quad R^2=0.8908 \quad \text{(Layer 3 & 5, stiff to very stiff clay)} \]  
\[ s_{u,\text{UU}} = 19.597 + 0.943z, \quad R^2=0.6937 \quad \text{(Layer 3 & 5, stiff to very stiff clay)} \]  
\[ s_{u,\text{CU}} = 15.094 + 3.438z, \quad R^2=0.9651 \quad \text{(Layer 3 & 5, stiff to very stiff clay)} \]

Large differences are observed between the organic clay layer and clay layer due to the different physical states, which might be represented by the liquidity index. It is more suitable to use effective vertical pressure \( \sigma_0' \) to normalise undrained shear strength \( s_u \).

**Figure 4. Undrained shear strength of Tra Vinh Clay**

Figure 5a presents the normalised undrained shear \( s_u / \sigma_0' \) profile strength with depth, organic clay at 0m to 10m depth is heavily overconsolidated, where the overconsolidation ratio (OCR) decreases sharply with the increasing depth, indicates that organic clay in this depth is normally consolidated or slightly overconsolidated. For Tra Vinh Clay (Layer 3&5), \( s_u / \sigma_0' \) of UU and Qu test is much lower than that of CU and DSq from 20m to 80m depth, sample disturbance has a very huge effect on soil strength. From the CU and DSq test results, \( s_u / \sigma_0' \) at 20m to 40m depth is slightly larger than that of clay below 40m, which means that clay at 20m to 40m should be overconsolidated. With depth increases, the clay becomes normally consolidated.

To minimize the influence of the OCR, and find the relationship between the liquidity index \( I_L \) and \( s_u / \sigma_0' \), \( s_u / \sigma_0' \) of organic clay at 0m to 10m depth and 20m to 40m with high OCR are eliminated. Considering that undrained shear strengths of UU and Qu tests are underestimated, only DSq and CU tests results for both organic clay and clay are plotted in Figure 5b. Due to lack of results, the linear regression of CU tests is not well enough comparing to the regression of DSq test. As shown in Figure 5b, although the undrained shear strength of Tra Vinh organic clay is much lower than the strength of Tra Vinh clay, it is clearly that a negative linear correlation is existed between liquidity index \( I_L \) and
$s_u/\sigma_v'$ from DSq test results, with $R^2=0.8935$. Liquidity index cloud be a crucial factor that represents the physical and mechanical properties of clay, where organic matter content has less effect on the mechanical properties of clay. The regression equation is as follows:

$$(s_u / \sigma_v')_{DSq} = 0.4058 - 0.2189I_L, \quad R^2=0.8935$$

(7)

By substituting average liquidity indexes of Layer 2, Layer 3 and Layer 5 into equation (7), $s_u/\sigma_v'$ for three layers are cautiously evaluated in Table 4.

Table 4. Normalised undrained shear strength $s_u/\sigma_v'$ evaluation for Tra Vinh Clay

| Soil layer | Layer 2 (Organic Clay) | Layer 3 (Clay) | Layer 5 (Clay) |
|------------|-------------------------|----------------|----------------|
| Liquidity Index $I_L$ | 1.064 | 0.289 | 0.277 |
| $s_u/\sigma_v'$ | 0.1729 | 0.3425 | 0.3510 |

3.3. Undrained shear strength interpretation by CPTU

Piezocone penetration test (CPTU) is one of the most popular in-situ tests to evaluate soil strength. Several interpretation methods have been established to interpret the undrained shear strength [13]. $N_{kt}$ method is commonly used, which can be expressed as follows:

$$s_u = \frac{q_t - \sigma_v}{N_{kt}}$$

(8)

where $q_t$ is the corrected cone resistance, $\sigma_v$ is total vertical stress, $N_{kt}$ is an empirical coefficient, which has a very wide range of 7 to 29 [14].

Without any experience or previous research data, it is difficult to choose appropriate $N_{kt}$ value for CPTU interpretation. Lunne et al. [3] proposed an OCR related expression with $q_{net}$:

$$\frac{(s_u/\sigma_v')_{CU} - 0.05026}{0.1027I_L} + 0.207$$

$R^2=0.2464$

$$\frac{(s_u/\sigma_v')_{Dsq} - 0.4058 - 0.2189I_L}{0.8935}$$

$R^2=0.8935$

Figure 5. Normalised undrained shear strength $s_u/\sigma_v'$ of Tra Vinh Clay
where \( k \) is a parameter of value 0.2 to 0.5 [13], which can be cautiously assumed as 0.2.

By combining equation (8) and equation (9), undrained shear strength can be interpreted by:

\[
\frac{S_u}{\sigma_{v0}'} = a \cdot \left( 0.2 \cdot \frac{q_{int}}{\sigma_{v0}'} \right)^b
\]

where \( a \) and \( b \) are the empirical coefficients, which is theoretically equal to the \((s_u/\sigma_{v0})_{NC}\) and \((\lambda-\kappa) / \lambda\), respectively. The compression index \( \lambda \) and swelling index \( \kappa \) can be obtained by oedometer test, the CPTU interpretation parameters of Tra Vinh Clay are shown in Table 5 as below.

**Table 5. CPTU interpretation parameters for Tra Vinh Clay**

| Soil layer | Layer 2 (Organic Clay) | Layer 3 (Clay) | Layer 5 (Clay) |
|------------|------------------------|----------------|----------------|
| Compression index \( Cc \) | 0.1985 | 0.0880 | 0.0721 |
| Swelling index \( Cs \) | 0.0334 | 0.0172 | 0.0113 |
| \( A \) | 0.832 | 0.805 | 0.843 |
| \( s_u/\sigma_{v0}' \) | 0.1729 | 0.3425 | 0.3510 |

**Figure 6. Mechanical properties interpretation of clay by CPTU**

In-situ CPTU tests are carried out near the relevant borehole locations with a distance of no more than 5m. CPTU-11 (near Borehole 11) is selected to further analyse the \( s_u \) of Tra Vinh organic clay and clay. By combined SHANSEP and OCR-to-CPTU correlation, the undrained shear strength can be interpreted (Figure 6). As shown in Figure 6a, the interpretation of Layer 1 (organic clay) at 0m to 20m is consistent with laboratory test results, which preliminarily verified the applicability of combined SHANSEP and OCR-to-CPTU method, and also the interpretation results of clay at 45m to 55m show good agreement with laboratory test results. However, for clay about 30m to 40m and 60m
to 70m, CPTU interpretation is observed considerable difference from laboratory test results. The possible reason for the inconsistency could be the sample disturbance, which results in the reduction of the preconsolidation pressure, OCR and strengths of soil samples in laboratory tests. The OCR interpretation by CPTU is presented in Figure 6b. The OCR varies from 1.7 to 1.0 for organic clay from 9m to 20m, while the OCR varies from 1.4 to 1.0 for the clay layer at 44m to 56m, which means these two layers are nearly normally consolidated. For clay from 29.5m to 38.5m, OCR is nearly equal to 2.5, and OCR varies from 1.5 to 2.5 for clay from 57m to 70m, which means these two layers are overconsolidated. Due to sample disturbance, the OCRe of soil samples for laboratory tests will be certainly lower than the OCR of in-situ soil (even lower than 1.0 after disturbance). In direct quick shear and triaxial CU test, a reconsolidation process is carried out before shearing, the OCR of soil samples will be recovered to at least 1.0 (normally consolidated). Therefore, the laboratory test results of direct quick shear and triaxial CU would only be consistent with the normally consolidated clay layer. For overconsolidated clay layer, the laboratory test results of direct consolidated quick shear and triaxial CU would be lower than the in-situ strength (CPTU interpretation). That’s the reason why the laboratory test results of some clay layers are not consistent with the SHANSEP and OCR to CPTU interpretation.

For engineering projects, it is more convenient to use Nak method for CPTU interpretation. By taking the results of combined SHANSEP and OCR-to-CPTU method as reference, the Nak values for Tra Vinh organic clay and clay could be obtained. As presented in Figure 6, Nak of 25 and 17 could be reasonably chosen for CPTU interpretation of Tra Vinh organic clay and clay, respectively.

4. Discussion

Previous researches had established undrained shear strength su with liquidity index IL [11,15] and normalised undrained shear strength su/σOd with plasticity index Ip [16]. From this paper, the undrained shear strength is found to be approximated linear dependent on the soil depth (vertical stress), the relation between undrained shear strength and liquidity index might be only be used within a small deviation on soil depth. Establishing a relationship between normalised undrained shear strength su/σOd and liquidity index IL is more suitable and efficient for strength evaluation for the same kind of clay. For different kinds of clay, the relationship between normalised undrained shear strength su/σOd and liquidity index IL could be different. Because the normalised undrained shear strength is quite different with different kinds of clay.

Ladd [10] found that the normalised undrained shear strength of normally consolidated clay (su/σOd)NC varies from 0.162 to 0.25. From the data of clay in south China sea [17], the (su/σOd)NC varies from 0.1997 to 0.2271, where the data from clay in Norway [4] shown that the (su/σOd)NC varies from 0.301 to 0.340. In this paper, the normalised undrained shear strength (su/σOd)NC varies from 0.1729 to 0.3510. Based on these data, it is probable that the normalised undrained shear strength (su/σOd)NC has a wider range than expected. The (su/σOd)NC could be affected by the organic content, sand content, or other factors, which need further researches.

5. Conclusions

In this paper, laboratory tests and CPTU results in Tra Vinh V1-2 wind power project had been analysed. Three main clayey layers, Layer 2 (Soft organic clay), Layer 3 and Layer 5 (stiff to very stiff clay) are discovered in Tra Vinh coast, South Vietnam. The undrained shear strengths su of Tra Vinh organic clay and clay are both positive linear dependent on soil depth. From top to 10m, OCR values of heavily overconsolidated organic clay decrease sharply, while the organic clay is nearly normally consolidated at depth of 10m to 20m. For 20m to 40m, the Tra Vinh clay is also overconsolidated, it is more suitable to use normalised undrained shear strength su/σOd to evaluate the strength in Tra Vinh. By adopting SHANSEP method, the normalised undrained shear strength su/σOd of Tra Vinh clay exhibits a negative linear correlation of liquidity index su/σOd = 0.4058-0.2189/IL, the undrained shear strength of Tra Vinh clay can be rapidly and cautiously evaluated by substituting liquidity index IL into...
the expression. For Layer 2, 3 and 5, \( s_d/\sigma_0' \) can be reasonably chosen as 0.1729, 0.3425 and 0.3510, respectively.

Based on the normalised undrained shear strength \( s_d/\sigma_0' \) and oedometer test results, CPTU interpretation is carried out by combined SHANSEP and OCR-to-CPTU method, which shows a good agreement with laboratory test results of Tra Vinh organic clay at 0m to 20m, and reappears the in-situ undrained shear strength of Tra Vinh clay from 20m to 70m.

After calibration by taking the interpretation results of SHANSEP and OCR-to-CPTU method as a reference, \( N_{st} \) values of 25 and 17 are respectively recommended for Tra Vinh organic clay and Tra Vinh clay in the offshore area, which is more convenient for CPTU interpretation in engineering projects.

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6. References
[1] Bjerrum L 1954 Geotechnical properties of Norwegian marine clays. Géotechnique, 4 49-69
[2] Berre T 1986 Effect of sampling disturbance on undrained shear static triaxial tests on plastic

drammen clay. Norwegian Geotechnical Institute, NGI Report 56001-3.
[3] Lunne T, Berre T and Strandvik S 1997 Sample disturbance effects in soft low plastic

Norwegian clay. In Proceedings of the conference on Recent Developments in Soil and Pavement Mechanics (Rio de Janeiro:Brazil/ M. Almeida, A.A. Balkema) p 81-102
[4] Lunne T, Berre T, Andersen K H, Strandvik S and Sjursen M 2006 Effects of sample disturbance and consolidation procedures on measured shear strength of soft marine Norwegian clays. Can. Geotech. J. 43 726-750.
[5] Lukas W G, DeGroot D J, DeJong J T, Krage C P and Zhang G 2019 Undrained shear behavior of low-plasticity intermediate soils subjected to simulated tube-sampling disturbance. J. Geotech. Geoenviron. 145 04018098.
[6] Schofield A and Wroth P 1968 Critical state soil mechanics (New York: America/ McGraw-
hill)
[7] Wang L Z, Wang K J and Hong Y 2016 Modeling temperature-dependent behavior of soft clays J. Eng. Mech.-ASCE 142 04016054
[8] Wang K J, Wang L Z, and Hong Y 2020 Modelling thermo-elastic–viscoplastic behaviour of marine clay. Acta Geotech. 15 2415-2431
[9] Ladd C C and Footh R 1974 New design procedure for stability of soft soil. J. Geotech. Eng. Div. -ASCE 100 736-786
[10] Ladd C C 1991 Stability Evaluation during Staged Construction. J. Geotech. Eng.-ASCE, 117 540-615
[11] Vardanega P J and Haigh S K 2014 The undrained strength – liquidity index relationship. Can. Geotech. J. 51 1073-1086.
[12] Kuriakose B, Abraham B M, Sridharan A, Jose B T 2017 Water content ratio: an effective substitute for liquidity index for prediction of shear strength of clays. Geotech. Geol. Eng. 35 1577-1586
[13] Kuriakose B, Abraham B M, Sridharan A, Jose B T 2017 Water content ratio: an effective substitute for liquidity index for prediction of shear strength of clays. Geotech. Geol. Eng. 35 1577-1586
[14] Robertson P K and Cabal K L 2015 Guide to cone penetration testing for geotechnical engineering. Gregg Drilling & Testing, Inc. 6.
[14] Liu K, and Wang J H 2017 Evaluation on undrained shear strength of marine soil using cone penetration resistance in Zhujiang River mouth basin, South China Sea. *Indian J. Geo-Mar. Sci.* **45** 707-718.

[15] Yilmaz I 2000 Evaluation of shear strength of clayey soils by using their liquidity index. *B. Eng. Geol. Environ.* **59** 227-229.

[16] Das B M 1994 Principles of geotechnical engineering. PWS, Boston, 672

[17] Zhou S W, Zhou Y R, Li Y, Zhang W, Dong M M, Liu S S 2014 Evaluation of the strength of offshore cohesive soils by SHANSEP method based on Direct Simple Shear test. *Mar. Sci. B.* **33** 328-332 (In Chinese)