The Undrained Shear Strength Evaluation of Vinh Chau Clay in Vietnam Coast

Weilong Wang1,2, Wenbo Du2,3, Kuanjun Wang2,3* and Zhenhong Wang3

1 The Architectural Design & Research Institute of Zhejiang University Corporation Limited, Hangzhou, Zhejiang Province, China
2 POWERCHINA Huadong Engineering Corporation Limited, Hangzhou, Zhejiang Province, China
3 Zhejiang Huadong Construction Engineering Corporation Limited, Hangzhou, Zhejiang Province, China
Email: Wang_kj@ecidi.com

Abstract. In the foundation design, the geotechnical engineering parameters are of great importance. As a case study, the laboratory test results of two locations (Banpu and Lac Hoa) in Vinh Chau coast of Vietnam were analysed to acquire the accurate strength for clayey soil. Due to the sample disturbance, the undrained shear strength $s_u$ from unconfined compression test are not so reliable, while $s_u$ from direct quick shear tests (DSq) are more representative in Vinh Chau. A regression analysis between the DSq tests and soil depth had been carried out, good linear correlations are provided for all the three clayey layers in Banpu and Lac Hoa, the results are relatively similar for each clay layer, indicating a same sedimentary and stress history. Furthermore, the normalised undrained shear strengths $s_u/\sigma'_v$ presented negative linear correlation of liquidity index, and the regression equations have been provided to rapid and cautious estimation of Vinh Chau clay in the future, using the liquidity index.

Keywords. Vinh Chau clay, OCR, normalised undrained shear strength, liquidity index.

1. Introduction
The geotechnical engineering parameters of clayey soil are of significant effect on the foundation design. Due to the disturbance of borehole sampling and transportation [1-5], the strength obtained by the laboratory test results of disturbed samples are much lower than the strength of the in-situ clay, especially for unconsolidated triaxial undrained shear test (UU) and unconfined compression test (Qu). Using these unconsolidated undrained shear strengths obtained by UU and Qu test results would lead to a huge waste in foundation design. Hence, how to accurately evaluate the precise undrained shear strength of clay becomes a problem. Theoretical method, such as Modified Cam Clay model [6] and other models [7-9] had already been used in evaluation the undrained shear strength, by establishing the normalised undrained shear strength of normally consolidated ($s_u/\sigma'_v$)$_{NC}$ and OCR. Actually, the OCR cannot be precisely obtained through one-dimensional compression test by using disturbed sample. Therefore, the theoretical method is difficult to evaluate the undrained shear strength of in-situ clay. Some researches had using the consolidated direct quick shear test (DSq) and consolidated triaxial undrained shear test (CU) results to evaluate the soil strength [10-11], and established the relationship between the physical properties and the undrained shear strength [12-14]. In this paper, the consolidated direct quick shear test (DSq) test, and unconfined compression test (Qu) test are carried out at Vinh Chau coast area in Vietnam. Linear regression between the undrained shear
strength and clay depth has been established. And the recommended normalised undrained shear strengths of Vinh Chau clay have also been provided, which can be used for rapid evaluation for the Vinh Chau clay in the future.

2. Physical Properties of Vinh Chau Clay

2.1. Site Overview
Lac Hoa wind power project is located in Lac Hoa Commune, Vinh Chau District, Soc Trang Province, which is 5.5 km away from the downtown Vinh Chau. Banpu wind power project is located in Vinh Phuoc Ward, Vinh Chau District, which is relatively near Lac Hoa with only 8.7 km. As shown in figure 1, both the projects are near the Vietnam coast, which is situated in south of Vietnam.

![Figure 1. Locations of the wind power project in Vietnam coast](image)

2.2. Soil Conditions
10 and 16 boreholes are drilled respectively in Banpu and Lac Hoa projects. Clayey soil samples are taken by thin walled tube sampler, with a diameter of 76mm, according to ASTM D1587. The classifications of all the soil samples are strictly followed the requirements of ASTM D2487. The soil conditions of Banpu and Lac Hoa are relatively similar, which are consisted of three clayey soil layers from the top to 80m depth, and an interbedded sand layer (Lense 2a) in Layer 2 (Clay). The overview of soil strata and geotechnical characterisation are shown in table 1.

| No.   | Soil type                          | Banpu Top [m] | Banpu Bottom [m] | Lac Hoa Top [m] | Lac Hoa Bottom [m] |
|-------|------------------------------------|---------------|------------------|----------------|-------------------|
| Layer 1 | Organic clay, very soft           | 0             | 16.0~20.1        | 0              | 19.5~21.7         |
| Layer 2 | Clay, firm to stiff              | 16.0~21.5     | 28.5~63.5        | 19.5~22.4      | 51.5~66.0         |
| Lense 2a | Clayey sand, loose to medium dense | 29.5~45.5   | 33.6~48.0        | 35.5~39.5      | 36.5~48.0         |
| Layer 3 | Clay, very stiff to hard         | 48.0~67.3     | 72               | 51.5~66.0      | 60.0~79.0         |
2.3. Physical Properties

Figure 2 presents the plasticity chart for the clayey soil in Vinh Chau coast, most of the clayey soil samples are in CL/OL (Low plasticity clay or organic clay) and CH/OH (High plasticity clay or organic clay), few soil samples are in of ML/OL (Low plasticity silt or organic silt) and MH/OH (High plasticity silt or organic silt). The physical properties for the three layers are summarized in table 2.

Table 2. Physical properties of Vinh Chau clay.

| Layer   | Grained size distribution | Physical properties | Banpu    | Grained size distribution | Physical properties |
|---------|---------------------------|---------------------|----------|---------------------------|---------------------|
|         | Sand (%)                  | Silt (%)            | Clay (%) | w (%)                     | Lp (%)              | Il (%)              | w (%) | e0   | ρ (g/cm³) | Gs   |
| Layer 1 | 1.2                       | 43.3                | 55.5     | 54.4                      | 30.7                | 1.131               | 58.4   | 1.616 | 1.610     | 2.655 |
| Layer 2 | 10.8                      | 52.3                | 36.9     | 44.7                      | 22.5                | 0.516               | 33.7   | 0.953 | 1.848     | 2.692 |
| Layer 3 | 11.6                      | 45.3                | 43.1     | 48.6                      | 26.5                | 0.262               | 29.1   | 0.854 | 1.886     | 2.704 |
| Lac Hoa | Grained size distribution | Physical properties |         |                           |                     |                     |        |       |           |       |
| Layer 1 | 5.5                       | 50.9                | 43.6     | 48.5                      | 26.4                | 1.145               | 52.5   | 1.463 | 1.643     | 2.651 |
| Layer 2 | 6.1                       | 58.4                | 35.5     | 44.9                      | 22.1                | 0.495               | 33.8   | 0.948 | 1.854     | 2.691 |
| Layer 3 | 6.9                       | 52.1                | 41.0     | 46.1                      | 25.5                | 0.246               | 27.0   | 0.776 | 1.928     | 2.689 |

From the grained size distribution, the particle sizes of Layer 2 and Layer 3 in Banpu and Lac Hoa are relatively similar, where the clay content of Layer 1 in Banpu is higher than Lac Hoa. But the physical properties show that the Atterberg limits, specific gravity, water content and natural density of all the three layers are almost the same, only the initial void ratios of Layer 1 have a certain difference of 0.153. In general, it is practicable to consider the clay in Banpu and Lac Hoa as the same kind of soil.

3. Undrained Shear Strength Evaluation

3.1. Sample Quality

During the effects of drilling and transportation, the clayey soil samples’ mechanical parameters are strongly disturbed. The volumetric strain \( \varepsilon_{\text{vol, c}} \) [15] and pore volume relative to the initial pore volume \( \Delta e/e_0 \) [3] had been proposed to qualify the sample disturbance (table 3). The latter had been found to
be more representative for the disturbance evaluation, which had been successfully applied to the disturbance evaluation of Nile delta clay [16].

(a) Banpu

(b) Lac Hoa

Figure 3. Sample disturbance evaluation for clayey soil in Vinh Chau coast.

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

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

Figure 3 present the $\Delta e/e_0$ of all the clayey soil samples, with 276 and 375 samples in Banpu and Lac Hoa, respectively. In Banpu, only 2.5% Level 1 and 4.0% Level 2 samples are obtained from the drilling boreholes, with 41.3% Level 3 and 43.1% Level 4 samples. The sample qualities in Lac Hoa are relatively better, with 5.8% Level 1, 12.0% Level 2, 55.4% Level 3 and 39.1% Level 4 samples are obtained. The Level 1 and Level 2 samples are mostly distributed from 0m to 15m depth, which is consistent with the results of Onsoy clay in Norway [4]. With the increasing depth, the samples are more likely to be disturbed, especially for the soft organic clay between 10m to 20m, due to the higher sensitivity than the stiff clay below.

3.2. Undrained Shear Strength from DSq and Qu Tests

Direct quick shear test (DSq) and unconfined compression test (Qu) are carried out to obtain the undrained shear strength in Banpu and Lac Hoa. Figure 4 provides the DSq and Qu test results of organic clay and clay, the unconfined compression test results for Layer 1 (organic clay) reveal a linear relationship between undrained shear strength and soil depth, however, with the increasing soil depth, no significant correlation is found between the soil depth and undrained shear strength for Layer 2 (firm to stiff clay) and Layer 3 (very stiff clay). It seems possible that with the increasing soil depth, the disturbances of samples are also increasing, which result in the dispersity of the undrained shear strength, especially in the depth deeper than 40m. Unlike the Qu test results, the DSq results indicate an obviously positive correlation between the depth and the undrained shear strength for all layers separately. The reason for this might be due to the consolidation process before quick shearing of the DSq test, where the consolidation process will reduce the effect of the sample disturbance. From the results of DSq test, the undrained shear strengths of clayey soil are found to be linear dependent on the soil depth, which is consistent with the earlier observations [17], and also soil type dependent. The linear expressions for all the clayey layers in Banpu and Lac hoa are shown in the following:

$$\sigma_{u,DSq} = 7.022 + 0.512z$$ (Layer 1, organic clay, Banpu) (1a)
The expressions between Banpu and Lac Hoa show slight differences for each layer, which means the sedimentary histories of the two locations in Vinh Chau are similar. However, huge differences are observed between the different layers, the possible explanation for the differences could be attributed to the different soil strength states, which might be represented by the liquidity index. In order to uncover the reason causing the difference, the undrained shear strengths are normalised by the effective vertical pressure $\sigma_{v0}'$. The next section is concerned with the undrained shear strength after normalisation.

3.3. Normalised Undrained Shear Strength

Figure 5 provides the normalised undrained shear strength of Banpu and Lac Hoa, as presented from the results of Layer 1, the organic clay at the depth from 0m to 10m is obviously overconsolidated, the overconsolidation ratio decreases sharply with the depth. At the depth from 10m to 20m, the $s_u/\sigma_{v0}'$ of organic clay are almost the same, indicating that the organic clay is normally consolidated or slightly overconsolidated. For layer 2, the $s_u/\sigma_{v0}'$ of the clay at 20~25m are slightly larger than the $s_u/\sigma_{v0}'$ of the clay below 25m, which means the clay at 20~25m is surely overconsolidated, with the increasing depth to the interface between Layer 2 and Layer 3, the clay
becomes normally consolidated. In contrast to Layer 1 and 2, the Layer 3 can be assumed to be normally consolidated, because no significant changes are found of $s_u/\sigma_{v0}'$ in Layer 3 with the increasing depth.

![Figure 5](image_url)

**Figure 5.** Normalised undrained shear strength $s_u/\sigma_{v0}'$ of the three clayey layers in Vinh Chau coast.

3.4. Relationship between the Liquidity Index and Normalised Undrained Shear Strength

It is rather complicated if the overconsolidation ratio is taken into consideration when researching the relationship between the strength and the liquidity index. In order to minimize the influence of the OCR, and find the relationship between the liquidity index and $s_u/\sigma_{v0}'$, the $s_u/\sigma_{v0}'$ of organic clay from 0m to 10m are eliminated, where the OCRs are relatively high. Figure 6 presents the $s_u/\sigma_{v0}'$ versus the liquidity index of the samples for all the three layers, by eliminating the data point of heavily consolidated clay. From the data in figure 6, it is apparent that the normalised undrained shear strength $s_u/\sigma_{v0}'$ has a clear decreasing trend of increasing liquidity index for normally consolidated or perhaps slightly overconsolidated clay. Interestingly, although the undrained shear strengths of organic clay are much lower than the $s_u$ of Layer 2 and 3, after the normalisation, the $s_u/\sigma_{v0}'$ also show surprising correlation with the liquidity index, which means the organic matter content will not directly influence the undrained shear strength, the liquidity index cloud be the main factor that represents both the physical and mechanical properties of clay.

The banpu clay presents a good quality of linear fitting with $R^2=0.8677$, where the fitting quality of Lac Hoa clay is slightly worse, but in an acceptable range with $R^2=0.7704$ higher than 0.5, the best linear regressions of Banpu and Lac Hoa clay are provided as follows:

$$s_u/\sigma_{v0}' = 0.4033 - 0.1894 I_L \quad (R^2=0.8677, \text{Banpu})$$  \hspace{1cm} (4)

$$s_u/\sigma_{v0}' = 0.3644 - 0.1464 I_L \quad (R^2=0.7704, \text{Lac Hoa})$$  \hspace{1cm} (5)
Figure 6. Relationship between $I_L$ and normalised undrained shear strength $s_u/\sigma_{v0}'$ of Vinh Chau clay.

The parameters of expressions for Banpu and Lac Hoa have a slight difference of 0.4, when the liquidity index of clay is around 0 (the water content is nearly equal to the plastic limit). With the increasing liquidity index, the normalised undrained shear strength $s_u/\sigma_{v0}'$ becomes closer, when the $I_L$ equals to 1.0, the $s_u/\sigma_{v0}'$ of Banpu and Lac Hoa are 0.2139 and 0.2180, respectively. This observation may support that the organic clay in Banpu and Lac Hoa are relatively consistent, the sedimentary and stress history of the organic clay layer are similar. For the stiff clay and very stiff clay with lower liquidity index below the organic clay layer, a certain strength difference has been observed, indicating that the sedimentary and stress history are of little difference. After all, it is possible to evaluate the undrained shear strength by using the liquidity index, if only physical properties of clay are available in Vinh Chau coast. It worth noting that the equations are only available for normally consolidated and lightly overconsolidated clay in Vinh Chau, for heavily overconsolidated clay, the equations (4) and (5) would be overly underestimated, but the equations are still acceptable for cautious estimate in engineering projects. The $s_u/\sigma_{v0}'$ for the three layers are cautiously evaluated in table 4 by using the equations (4) and (5), which can be used for rapid evaluation for the clay in Vinh Chau.

Table 4. Normalised undrained shear strength $s_u/\sigma_{v0}'$ evaluation for Vinh Chau Clay.

| Layer | Banpu | Lac Hoa |
|-------|-------|---------|
|       | $I_L$  | $s_u/\sigma_{v0}'$ | $I_L$  | $s_u/\sigma_{v0}'$ |
| 1     | 1.131 | 0.1891   | 1.145 | 0.495  |
| 2     | 0.516 | 0.3056   | 0.495 | 0.246  |
| 3     | 0.262 | 0.3537   | 0.246 | 0.3284 |

4. Conclusions

The DSq and Qu test results in Banpu and Lac Hoa of Vinh Chau coast have been analysed in this paper. Three main clayey layers, i.e. Layer 1 (Soft organic clay), Layer 2 (Firm to stiff clay), Layer 3 (Very stiff clay) are distributed in Banpu and Lac Hoa. The Layer 1 organic clay in Banpu and Lac Hoa has same sedimentary history, stress history and strength characteristic. The OCRs of organic clay decrease sharply with the increasing soil depth, where the undrained shear strengths are linear dependent on the soil depth. Little strength differences of the clayey layers below organic clay layer have been observed. Despite of that, the $s_u$ of three layers in Banpu and Lac Hoa have been confirmed to be depth dependent, which supports the previous findings of other researches, and the correlation expressions have been put forward of these clayey layers for rapid evaluation in future engineering projects.

Furthermore, the normalised undrained shear strengths $s_u/\sigma_{v0}'$ of all the clay exhibit obvious negative linear correlation of liquidity index, where the expressions are $s_u/\sigma_{v0}' = 0.4033 - 0.1894I_L$ and $s_u/\sigma_{v0}' = 0.3644 - 0.1464I_L$ for Banpu and Lac Hoa respectively. Finally, the undrained shear strength in Vinh Chau can be rapidly and cautiously evaluated by substituting the liquidity index into the expressions. For Layer 1, 2 and 3 in Banpu, $s_u/\sigma_{v0}'$ can be reasonably chosen as 0.1891, 0.3056 and
0.3537, respectively; for Layer 1, 2 and 3 in Lac Hoa, \( s_u/\sigma_v' \) can be reasonably chosen as 0.1968, 0.2919 and 0.3284, respectively, which are more convenient for geotechnical engineers to use.

Acknowledgments
The authors gratefully acknowledge the supports of the Zhejiang Provincial Natural Science Foundation of China (Grant No. LQ20E090001 and LQ19E090002), Key Science and Technology Plan of POWERCHINA Huadong Engineering Corporation (Grant No. KY2018-ZD-01) and Science and Technology project of POWERCHINA Huadong Engineering Corporation (Grant No. KY2020-KC-01 and KY2016-02-47).

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 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, Dan H B and Li L L 2012 Modeling strain-rate dependent behavior of \( K_o \)-consolidated soft clays J. Eng. Mech.-ASCE 138 738-48
[8] Wang L Z, Wang K J and Hong Y 2016 Modeling temperature-dependent behavior of soft clays J. Eng. Mech.-ASCE 142 04016054
[9] Wang K J, Wang L Z and Hong Y 2020 Modelling thermo-elastic–viscoplastic behaviour of marine clay Acta Geotech. 15 2415-2431
[10] Ladd C C and Foor R 1974 New design procedure for stability of soft soil J. Geotech. Eng. Div.-ASCE 100 736-786
[11] Ladd C C 1991 Stability Evaluation during Staged Construction J. Geotech. Eng.-ASCE, 117 540-615
[12] Vardanega P J and Haigh S K 2014 The undrained strength – liquidity index relationship Can. Geotech. J. 51 1073-1086.
[13] Yilmaz I 2000 Evaluation of shear strength of clayey soils by using their liquidity index B. Eng. Geol. Environ. 59 227-229
[14] 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. Geolo. Eng. 35 1577–1586
[15] Andresen A and Kolstad P 1979 The NGI 54mm samplers for undisturbed sampling of clays and representative sampling of coarser material Proceedings of the International Symposium on Soil Mechanics and Foundation Engineering (Singapore/ Japanese Society of Soil Mechanics and Foundation Engineering) p 13-21
[16] Hight D W, Hamza M M and El Sayed A S 2002 Engineering characterization of the Nile Delta clays Proceedings of the International Symposium 2 (Yokohama: Japan/ A.A. Balkema) p 149-162
[17] Mesri G 1989 A reevaluation of \( s_{u(mob)} = 0.22\sigma_p' \) using laboratory shear tests Can. Geotech. J. 26 162-164.