Shear strength assessments of residual soil for Ia Pet wind power project in Vietnam

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Abstract. The geotechnical parameters are of great importance in wind turbine foundation design. As a case study, laboratory test results of Ia Pet wind power project in Vietnam were analysed to accurately estimate the strength of residual soil, which is classified as high plasticity silt (MH). Due to sample disturbance, the undrained shear strength $s_u$ from triaxial unconsolidated undrained shear test (UU) is absolutely underestimated, while $s_u$ from direct quick shear tests (DSq) and triaxial consolidated undrained shear test (CU) are more representative. Good linear correlations have been found between soil depth and strength obtained from DSq and CU tests. The normalised undrained shear strengths $s_u/\sigma_0'$ indicate that the residual soil at 0m to 8m is heavily overconsolidated, where $s_u/\sigma_0'$ is larger than 0.4. Furthermore, the normalised undrained shear strengths $s_u/\sigma_0'$ presented negative linear correlation of liquidity index, which can be used to quick and cautious estimate the strength of Ia pet residual soil in the future by using liquidity index. The undrained shear strength evaluation using liquidity index is in good agreement with DSq and CU test results, which preliminarily verifies the applicability of expression between $s_u/\sigma_0'$ and $I_L$.

1. Introduction
Mechanical properties of clayey soil have significant effect on foundation design. Due to sample disturbance of drilling and transportation [1-4], the laboratory test results of disturbed samples are much lower than real strength of in-situ soil, especially for unconsolidated undrained shear test (triaxial UU test), which would lead to an extremely conservative foundation design. How to evaluate the precise undrained shear strength of in-situ clayey soil becomes a key point. Theoretical method [5-8] had already been used in strength evaluation by establishing normalised undrained shear strength of normally consolidated ($s_u/\sigma_0'$)$_{NC}$ and overconsolidation ratio (OCR). However, OCR cannot be precisely obtained through one-dimensional compression test of disturbed sample. Ladd and Foot [9] had using SHANSEP (Stress History and Normalized Soil Engineering Properties) method to minimize the sample disturbance. Some researchers [11-13] established the relationship between physical properties and...
undrained shear strength, the soil strength could be rapidly estimated by using physical properties and the strength correlation. In this paper, the consolidated direct quick shear test (DSq) test, unconsolidated undrained shear test (triaxial UU test) and consolidated undrained shear test (triaxial CU test) are carried out on residual soil at Ia Pet wind power project in Vietnam. Linear regression between undrained shear strength and depth has been established. Correlation between normalised undrained shear strength \( \left( \frac{s_u}{\sigma_{v0}} \right) \) and liquidity index \( I_L \) of Ia Pet silt has also been provided, which could be used for rapid evaluation for Ia Pet silt in the future.

2. Physical properties of Ia pet residual soil

2.1 Site overview

The Project of Ia Pet wind power project is located in territory of Trang (Figure 1), Ia Pet and Glar communes, Dak Doa district, Gia Lai province. The Ia Pet wind power project in the SouthEast direction of Pleiku city with about 17km distances, and about 11km south of Dak Doa district center.

2.2 Soil conditions

The Ia Pet project is located on a low mountainous-cleaved terrain with a ground elevation in a range from 700m to 750m. 31 boreholes with 40m depth are drilled in Ia Pet projects, which are performed in accordance with Vietnam standard TCVN 9437-2012. Hydraulic drilling equipment and drilling bit with minimum diameter of 76mm has been used, sampling, curing and transporting samples are carried out in accordance with Vietnam standard TCVN 2863-2012.

The classifications of all the soil samples are comply with the requirements of ASTM D2487. Two residual soil layers are encountered from 0 to 40m. Layer 1 Eluvial-deluvial zone includes reddish brown clay and silt, which is completely weathered from basalt to residual soil. Layer 2 very strongly weathered zone includes reddish brown clay and silt. The grained size distributions of Ia Pet residual soil are listed in Table 1, which presents that the particle sizes of Layer 1 and Layer 2 in Ia pet wind power project are relatively similar. Figure 2 present the plasticity chart for the residual soil in Ia Pet project, the residual

| Particle Size | Gravel | Sand | Silt | Clay |
|---------------|--------|------|------|------|
| Size          | 4.75-9.5 | 0.425-2.0 | 0.075-0.15 | 0.002-0.005 |
| Layer 1       | 0.0     | 0.4   | 0.8  | 24.5 |
| Layer 2       | 0.1     | 0.4   | 1.2  | 23.5 |

Figure 1. Locations of Ia Pet wind power project in Vietnam

Table 1. Grained size distribution of Ia Pet residual soil
soil samples are classified in MH/OH (High plasticity silt or organic silt). The physical properties for two layers are summarized in Table 2.

![Casagrande plasticity chart for residual soil in Ia Pet wind power project](image)

**Figure 2. Casagrande plasticity chart for residual soil in Ia Pet wind power project**

| Physical properties | $w_t$ (%) | $I_p$ | $I_L$ (%) | $w$ (%) | $e_0$ | $\rho$ (g/cm$^3$) | $G_s$ |
|---------------------|-----------|-------|-----------|--------|-------|-----------------|-------|
| Layer 1             | 59.7      | 21.4  | 0.416     | 47.2   | 1.568 | 1.703           | 2.96  |
| Layer 2             | 74.0      | 23.4  | 0.134     | 53.8   | 1.694 | 1.694           | 2.96  |

The physical properties of Layer 1 and Layer 2 indicate that water content, void ratio, natural density and specific gravity of the two layers are almost the same. The liquid limits of Layer 1 and Layer 2 have a very large difference of 14.3, but very small difference of 2 in Plasticity index. It worth noting that liquidity indexes are also different between Layer 1 and Layer 2, which means the soil state of Layer 2 is much stiffer due to the higher overburden stress than Layer 2. Generally, it is acceptable to consider the Layer 1 and Layer 2 in Ia Pet as the same kind residual soil of MH (High plasticity silt).

### 3. Undrained shear strength assessment

#### 3.1 Sample quality

The mechanical properties of clayey soil are strongly dependent on the sample quality, which could be disturbed during drilling and sample transportation. Volumetric strain $\varepsilon_{vol,c}$ [14] and void ratio change relative to the initial void ratio $\Delta e/e_0$ [2] had been proposed to quantify the sample disturbance. $\Delta e/e_0$ had been found to be more representative for sample disturbance assessment.

| OCR | $\Delta e/e_0$ |
|-----|----------------|
| 1–2 | 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 show the sample disturbance assessment result part of residual soil samples from 31 drilling boreholes. Only 3.4% and 10.3% samples are classified as Level 1 and Level 2 samples, where 55.2%
and 31.0% of samples are classified as Level 3 and Level 4 samples, respectively. The Level 1 and Level 2 samples are distributed from 0m to 7m depth, samples are more likely to be disturbed with the increasing depth.

![Sample quality assessment for Ia Pet silt in Vietnam](image)

**Figure 3. Sample quality assessment for Ia Pet silt in Vietnam**

### 3.2 Undrained shear strength from Laboratory tests

Direct quick shear test (DSq), unconsolidated undrained shear test (UU) and consolidated undrained shear test (CU) are carried out to obtain the undrained shear strength of Ia Pet silt, where are presented in Figure 4.

![Undrained shear strength of residual soil (MH) in Ia Pet](image)

**Figure 4. Undrained shear strength of residual soil (MH) in Ia Pet**

![Normalised undrained shear strength $s_u/\sigma_{v0}'$ of residual soil in Ia Pet](image)

**Figure 5. Normalised undrained shear strength $s_u/\sigma_{v0}'$ of residual soil in Ia Pet**
The undrained shear strengths from all the laboratory tests are expected to linearly increase with soil depth. What stands out in Figure 4 is the extremely low UU test result comparing to DSq and CU test results. It seems possible that the low UU test results are caused by the sample disturbance. With the increasing depth, the UU test results become much lower than the DSq and CU test results, due to the increasing sample disturbance, which can be found in Figure 3. DSq are in good agreement with CU results, which indicate an obviously positive correlation between depth and undrained shear strength. The reason for this might be due to the consolidation process before shearing of CU and DSq test, which will reduce the effect of sample disturbance. The linear expressions for Ia Pet silt are shown as follows:

$$s_{u,DSq} = 8.32 + 5.95z, R^2 = 0.9143$$  

(1a)

$$s_{u,UU} = 23.43 + 1.16z, R^2 = 0.7179$$  

(1b)

$$s_{u,CU} = 25.35 + 5.10z, R^2 = 0.9309$$  

(1c)

The good linear relation between soil strength and soil depth indicates that the two soil layers have similar mechanical behaviour, but different physical property. In order to reveal the relation between mechanical behaviour physical properties, the effective vertical pressure $\sigma_{v0}'$ are adopted to normalise the undrained shear strength $s_u$.

Figure 5 provides the normalised undrained shear strength of Ia Pet silt, the $s_u/\sigma_{v0}'$ of silt from 0m to 8m is much higher than the $s_u/\sigma_{v0}'$ of silt below, some of which are even higher than 1.0. Because the $s_u/\sigma_{v0}'$ of normally consolidated soil are generally less than 0.4, therefore the silt at surface could be overconsolidated. The overconsolidation ratio (OCR) is decreasing sharply with the depth, and finally to 1.0 (normally consolidated).

3.3 Relationship between the liquidity index and normalised undrained shear strength

It is rather complicated if OCR is taken into account when analysing the relationship between strength and liquidity index. In order to minimize the influence of the OCR, the $s_u/\sigma_{v0}'$ data of silt from 0m to 8m depth are eliminated, where the silt is heavily overconsolidated. Figure 6 presents the $s_u/\sigma_{v0}'$, which are obtained from DSq test, versus liquidity index $I_L$, by eliminating the data of heavily overconsolidated silt. It is apparent that $s_u/\sigma_{v0}'$ has a clear decreasing trend with the increasing liquidity index. The liquidity index cloud be a main factor that represents the physical and mechanical properties of silt. The Ia Pet silt presents a fair quality of linear regression with $R^2=0.4171$, which are shown as follows:

$$s_u / \sigma_{v0}' = 0.4123 - 0.1532I_L \quad (R^2=0.4171)$$  

(2)
After all, it is possible to evaluate undrained shear strength by using liquidity index, if only physical properties of silt are available in Ia Pet. It worth noting that above equation is only suitable for normally consolidated and lightly overconsolidated silt in Ia Pet, not for heavily overconsolidated silt. Equation (2) could be overly underestimated, but still acceptable for cautious and quick estimate the silt strength in engineering projects. The $s_u/\sigma_{vo}'$ for Layer 1 and Layer 2 are cautiously evaluated in Table 4 by using the equations (2), which are also plotted in Figure 7a.

| Layer | Ia Pet |
|-------|--------|
|       | 1      | 2      |
| Average Liquidity Index $I_L$ | 0.416  | 0.134  |
| $s_u/\sigma_{vo}'$ | 0.3486 | 0.3918 |

Based on the 31 borehole logs, the average boundary depth between Layer 1 and Layer 2 is 16.25m, and the average ground water level is approximately 23.5m. The vertical stress $\sigma_{vo}'$ of Ia Pet silt from 0m to 40m can be directly calculated by using the average natural density of Layer 1 and Layer 2. The evaluated strength profile can be easily obtained by using the derived $s_u/\sigma_{vo}'$ value multiplying $\sigma_{vo}'$, the results are presented in Figure 7b. As shown in Figure 7b, the evaluation results are in good agreement with DSq and CU test results, which preliminarily verify the applicability of equation (2) in Ia Pet area.

4. Conclusions
DSq, UU and CU test results of residual soil (MH) in Ia Pet wind power project have been analysed in this article. The UU test results are much lower than DSq and CU test results due to the sample disturbance, which is increasing with soil depth. The undrained shear strength $s_u$ of two layers shows a good linear correlation with soil depth, and OCRs decrease sharply with the increasing soil depth, which supports the previous findings of other researches.
Furthermore, normalised undrained shear strength $s_u/\sigma_v'0$ of Ia Pet silt exhibits negative linear correlation of liquidity index, with an expression of $s_u/\sigma_v'0 = 0.4123 - 0.1532L_s$. The $s_u$ can be rapidly and cautiously evaluated by substituting liquidity index into the equation. For Layer 1 and Layer 2 in Ia Pet, $s_u/\sigma_v'0$ could be reasonably chosen as 0.3486 and 0.3918. Finally, an evaluated soil strength profile has been plotted, and shows good agreement with DSq and CU test results, which preliminarily verify the applicability of expression between $s_u/\sigma_v'0$ and $L_s$.

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

References
[1] Berre T 1986 Effect of sampling disturbance on undrained shear static triaxial tests on plastic Drammen clay. Norwegian Geotechnical Institute, NGI Report 56001-3.
[2] 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.
[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] Schofield A and Wroth P 1968 Critical state soil mechanics (New York: America/ McGraw-hill)
[6] Wang L Z, Dan H B and Li L L 2012 Modeling strain-rate dependent behavior of $K_0$-consolidated soft clays J. Eng. Mech.-ASCE 138 738-48
[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 Foot 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] Yilmaz I 2000 Evaluation of shear strength of clayey soils by using their liquidity index. B. Eng. Geol. Environ. 59 227-229
[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. Geolo. Eng. 35 1577–1586
[14] Andresen A and Kolstad P 1979 The NGI 54mm samplers for undisturbed sampling of clays and representative sampling of coarser material. In Proceedings of the International Symposium on Soil Mechanics and Foundation Engineering (Singapore/ Japanese Society of Soil Mechanics and Foundation Engineering) p 13-21.