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# Soil parameters for offshore wind farm foundation design: A case study of Zhuanghe wind farm

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ABSTRACT

The Zhuanghe wind farm is under development offshore China. The site investigation campaign was completed in 2019. Both monopiles and suction buckets are considered as foundation types, and they are presently in the design phase. Soil testing was carried out at both the HDEC and the NGI laboratories. Soil parameters obtained from the laboratory tests are interpreted and discussed in this paper. Important soil parameters for foundation design, such as static and cyclic shear strengths, shear modulus and thixotropy from the tests on the Zhuanghe soil are compared with available databases in the literature, and soil parameters for foundation design are recommended. The purpose of this study is to provide a realistic reference for research and practice in the offshore wind energy industry offshore China where very few advanced tests for windfarm development are available.

## 1. Introduction

The offshore wind energy market has been growing exponentially in the last 10 years. This development is due to huge and highly dispersed wind resources, demand for green and sustainable energy as well as the considerable cost reductions achieved in the recent years. In offshore wind farm projects, the cost of the foundations has been estimated to be about 25% to 35% of the overall costs of an offshore wind turbine (Bhattacharya, 2014). Soil parameters play a very important role in foundation design. Normally a range of soil parameters are required for offshore geotechnical design, including strength, deformation and consolidation characteristics (Lunne and Andersen, 2007). For example, the static undrained shear strength is a key parameter for checking foundation capacity. It can be determined from laboratory tests on soil samples and can be compared with the strength derived from in situ cone penetrometer (CPTU) tests. However, sample disturbance has to be evaluated, and representative shear strength profiles must be established. Remoulded shear strength and the shear strength increase after remoulding are important for installation and increase in capacity with time after installation. Clay along a driven pile or around a suction bucket is disturbed during installation. The shear strength after disturbance will increase with time, and it can increase by more than 100% due to thixotropy (Andersen and Jostad, 2002; Yang and Andersen, 2016), and excess pore pressure redistribution and dissipation. For offshore wind turbines, cyclic shear strength and stiffness degradation are needed in design for cyclic loads due to both wind and waves. Cyclic contour diagrams have been applied in offshore foundation design for many years (e.g. Andersen et al., 1988; Andersen and Høeg, 1991), and it is essential to check the capacity under cyclic loading and to evaluate if the cyclic displacement is tolerable (Andersen, 2015). The small strain shear modulus is a key soil parameter to estimate the eigenfrequency of offshore wind turbines and to evaluate the foundation performance in fatigue and serviceability limit states. A wider perspective of the type of soil parameters that are required for foundation design for different offshore foundation concepts are given in the literature (Andersen et al., 2008).

This paper presents a case study of soil parameters at the Zhuanghe offshore wind farm and evaluates several of the soil parameters that are important for the foundation design of offshore wind turbine foundations. The soil parameters are compared to existing data bases to explore to what extent existing data bases are valid for sites Offshore China, like the Zhuanghe site.

## 2. Soil conditions at Zhuanghe site

The Zhuanghe wind farm is located in the northern part of China,

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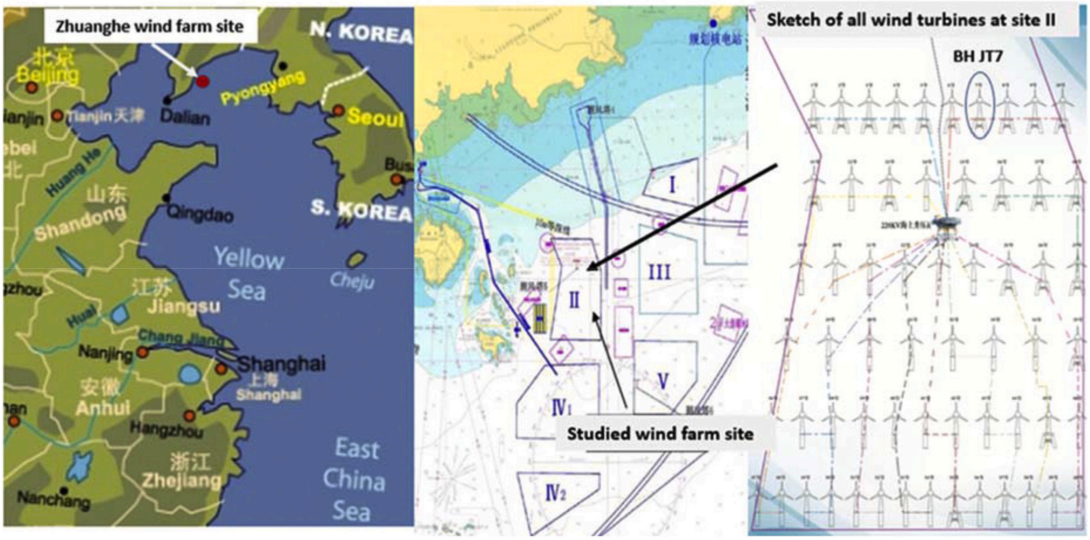


**Fig. 1.** Site location.

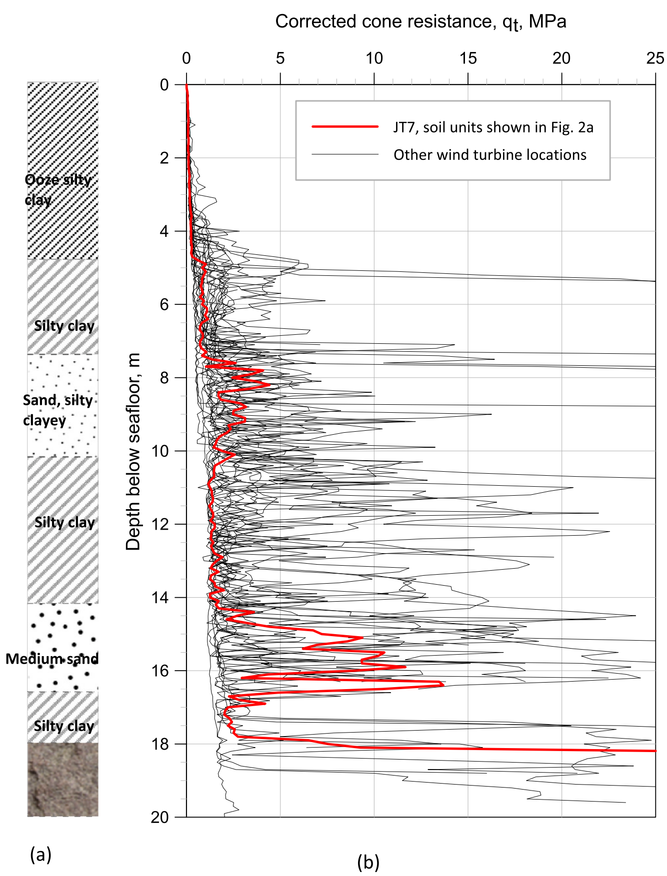


**Fig. 2.** (a) Typical soil units in the studied area (JT7), (b) Cone resistance from available CPTU tests.

near Dalian city (Fig. 1).

The water depth is around 16 m. Two rivers are located in the area, and they are the main controlling factors for the sedimentation environment (Liu and Yan, 2001; Zhang, 1987). Typical soil units in the upper 20 m is shown in Fig. 2 (a) from borehole location JT7. Available CPTU data is shown in Fig. 2 (b) for the whole wind farm site, including data from location JT7. At the windfarm site, the clay sedimentation environment is dominating in the upper about 5 m, and Ooze clay is discovered in the upper 5 m at most of the investigated locations. CPTU data shown in Fig. 2 (b) indicates that soils in the wind farm area has a big variation below about 5 m below seafloor. Soil classification from borehole JT7 is illustrated as an example in Fig. 3, based on the Robertson (1990) and (Robertson, 2016) methods. Clay is the dominating material along the depth in this borehole and thin sandy material is discovered too. The main soil units are ooze silty clay, silty clay, silty, clayey fine sand and medium sand according to Chinese standard (GB 50007-2002, 2002), and this classification system is used in this paper. Depth to weathered rock is at about 18 m at some locations, however the depth varies over the whole wind farm area. According to Chinese standard (GB 50007-2002, 2002), soil is defined as ooze if the water content is higher than the liquid limit and the void ratio is higher than 1.5. It is defined as ooze clay if the water content is higher than the liquid limit and the void ratio is between 1.0 and 1.5. The relative densities of sand layers are estimated based on CPTU data by using the Jamiolkowski et al. (2003) method (Fig. 4). Since there is a variation in the distribution of sand layers across the whole wind farm area, Fig. 4 includes all available CPTU data where a sand layer exists. In general, sand layers are in a medium dense to dense state. Suction buckets with skirt length around 10 to 15 m are considered as foundations for 20 of the wind turbines of the windfarm site, in addition to monopile foundations. In this paper, soil parameters in the upper 20 m below seafloor are mainly discussed.

## 3. Laboratory test program and index soil parameters

The main objective of the laboratory testing program is to obtain soil parameters for the most important soil units at the Zhuanghe site. Samples from borehole JT7 were delivered to the NGI laboratory in Oslo. Index tests, permeability tests, thixotropy tests, constant rate of strain consolidation tests (CRSC), monotonic and cyclic DSS with bender element tests, and monotonic triaxial tests were performed. In addition to the tests in the NGI laboratory, many index tests and a few UU and shear box tests were performed in the HDEC laboratory. The main index test results from the HDEC laboratory are shown in Fig. 5.

The water content is highest in the top ooze silty clay layer, ranging between 40% and 60%. Because offshore foundations will penetrate through this top layer and because it has a low shear strength, it will not contribute significantly to the capacity of the foundations. Only a few advanced tests were therefore performed in this ooze silty clay layer. The silty clay layer and the silty, clayey fine sand layers are more important for the foundation bearing capacity, and more advanced tests

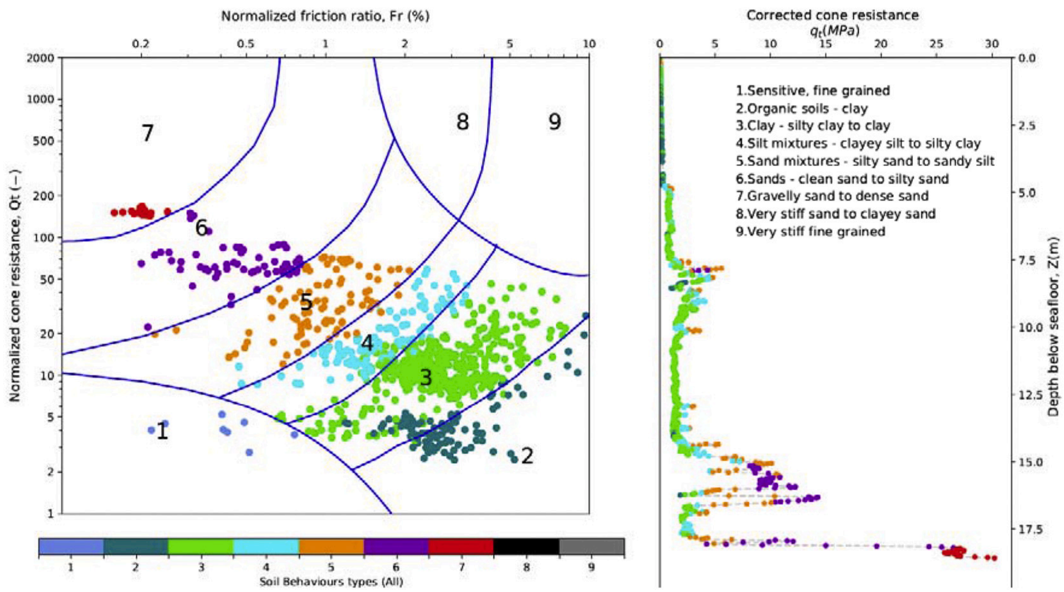


**Fig. 3.** Soil classification at JT7 based on Robertson (1990) and (Robertson, 2016).

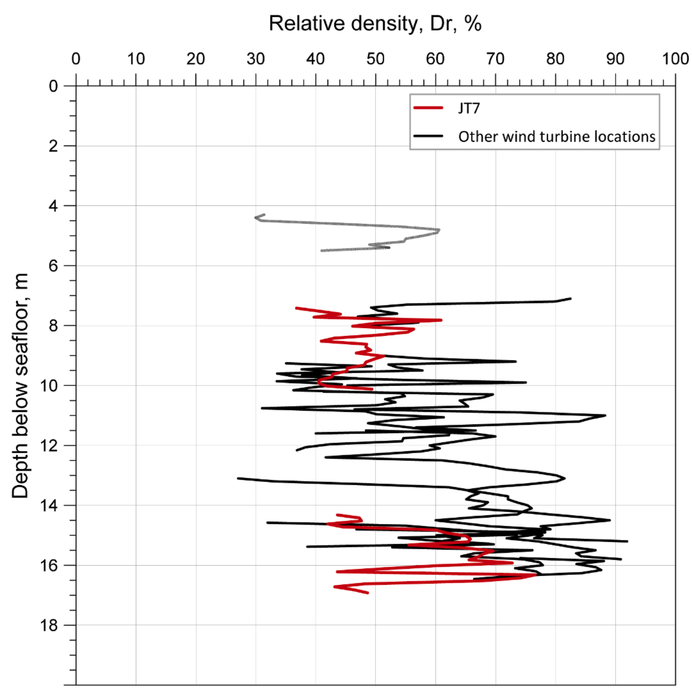


**Fig. 4.** Relative density for sand layers at the Zhuanghe site.

were done in these two layers. The relative density based on CPTU tests is shown in Fig. 4, including data from all available locations in the wind farm area. Basically, the upper silty, clayey sand is in a medium dense state, and the lower medium sand layer is in a medium dense state (ISO, 2004). For the upper silty, clayey sand layer, the silt content is close to 30% and the clay content is about 10%. This soil has been tested by using intact samples. No advanced tests were carried out on the medium dense sand layer. Both static and cyclic properties on this medium sand layer are estimated based on the NGI database in Andersen (2015) and will not be discussed further in this study.

Representative soil parameters for the soil units in borehole JT7 are listed in Table 1.

## 4. Thixotropy of the clays

Thixotropy can be described as a process of softening caused by remoulding, followed by a time dependent return to the original harder state at a constant water content and porosity. The ratio of the intact strength (prior to remoulding) to the remoulded strength immediately after remoulding is referred to as the sensitivity. The ratio between the shear strength after a time with thixotropic strength gain and the shear strength immediately after remoulding is referred to as the thixotropy strength ratio. Strength regain due to thixotropy can be important for clays, as it will increase the shear strength along the side of the foundation after installation.

Sensitivity and thixotropy tests by using fall cone were performed on the clays from borehole JT7 at depth 3.8–4.1 m in the ooze silty clay and

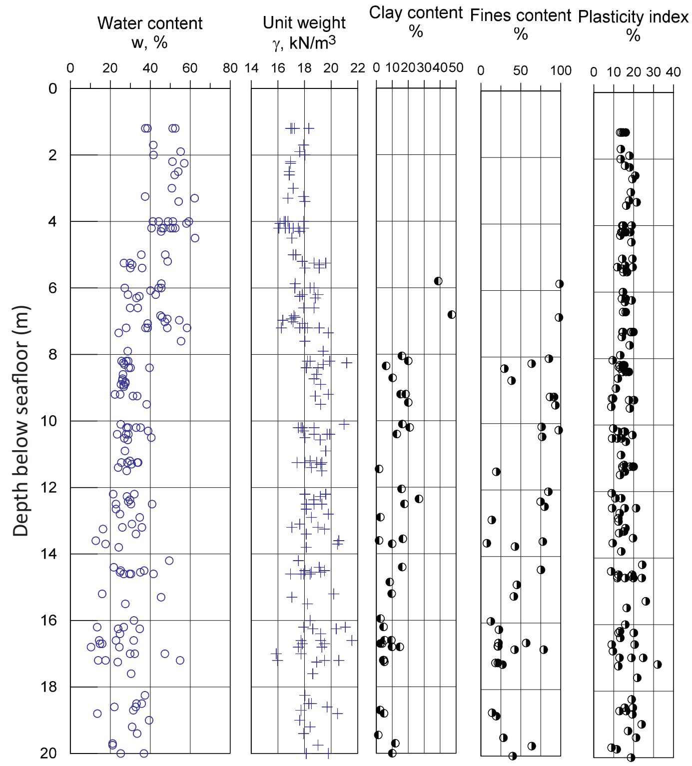


**Fig. 5.** Index properties of the soils in the upper 20 m below seafloor, tested at the HDEC laboratory.

**Table 1**
Representative soil parameters in BH JT7.

| Soil unit | Depth (m) | Water content (%) | Unit weight (kN/m$^3$) | Plasticity index (%) | Clay content (%) | Fines content (%) | $D_r$ for sand (%) | Sensitivity |
|---|---|---|---|---|---|---|---|---|
| 1Ooze silty clay | 0–4.8 | 59 | 16.2 | 14 | – | – | – | 3.7 |
| 2 Silty clay | 4.8–7.4 | 45 | 17.2 | 30–35 | 40–48 | 98–99 | | – |
| 3Silty, clayey, fine sand | 7.4–10 | 26 | 18.6 | 10 | 10.2 | 38.4 | 50–60 | |
| 4 Silty clay | 10–14 | 28 | 19 | 15–18 | 26.7 | 74.8 | – | 2.6 |
| 5Medium sand | 14–16.5 | 13 | 21 | | 4.5 | 22.6 | 60–85 | |
| 6Silty clay | 16.5–18 | 25 | 20 | 15 | 5* | 20* | – | – |

* From same soil layer in another location.

at depth 12.2–12.5 m in the silty clay layer.

Fig. 6 shows test results for the two clays in the Zhuanghe offshore wind farm compared to data from other offshore sites from other parts of the world. The top ooze silty clay shows higher strength regain after remoulding with time compared with the silty clay. In addition, the thixotropy ratio for ooze silty clay is on the high side of the results in the NGI database (Yang et al., 2020). These differences can be explained by the differences in sensitivity and liquidity index as shown in Fig. 7.

## 5. Static undrained shear strength

Undrained shear strengths from fall cone, DSS and triaxial tests at NGI, in addition to the UU and shear box tests at HDEC, are shown in Fig. 8. Undrained shear strength interpreted from CPTU with cone factors of $N_{kt}$ of 15 and 20 is also included in the figure too. Representative high and low undrained shear strengths for triaxial compression mode are proposed in the plot.

Table 2 shows a summary of all DSS test results, including index parameters. For the top ooze silty clay layer, the normalized DSS strength ratio is $s_{uD}/\sigma_{vc}' = 0.32$. Statistics for normalized undrained shear strength data showed that average normalized DSS strength ratio is 0.23 for soft clays (Lunne and Andersen, 2007). This value is higher for the Zhuanghe site. The difference is less if it is taken into account that the strength ratio, $s_{uD}/\sigma_{vc}'$, increases with decreasing consolidation stress, $\sigma_{vc}'$. The consolidation stress is only 28.4 kPa in the DSS test. The effect of consolidation stress can be accounted for by normalizing with the reference stress, $\sigma_{ref}' = 100\cdot(\sigma_{vc}'/100)^{0.9}$ (Andersen, 2015). This strength ratio becomes $s_{uD}/\sigma_{ref}' = 0.28$ for the top layer, which compares reasonably well with the $s_{uD}/\sigma_{ref}' = 0.25$ for normally consolidated Drammen clay, which has a plasticity index of 27% (Andersen, 2015). The reason for the higher strength ratio for the Zhuanghe test could be the accuracy in the data at the low consolidation stress in the test and that only one test has been performed. More tests are needed in order to get a more accurate representative value.

The SHANSEP procedure that was presented by Ladd and Foott (1974), may be helpful in this case. The SHANSEP procedure gives a general relationship between normalized undrained shear strength, overconsolidation ratio and maximum consolidation stress which can be assumed to be valid over a wide range of stresses. The SHANSEP procedure is valid for the following conditions:

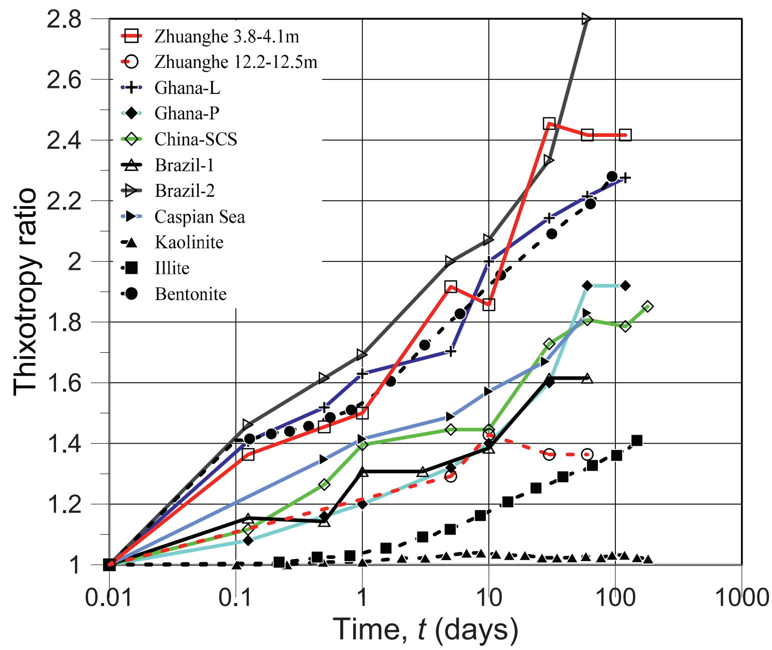


**Fig. 6.** Thixotropy strength ratio with time (After Yang et al., 2020).

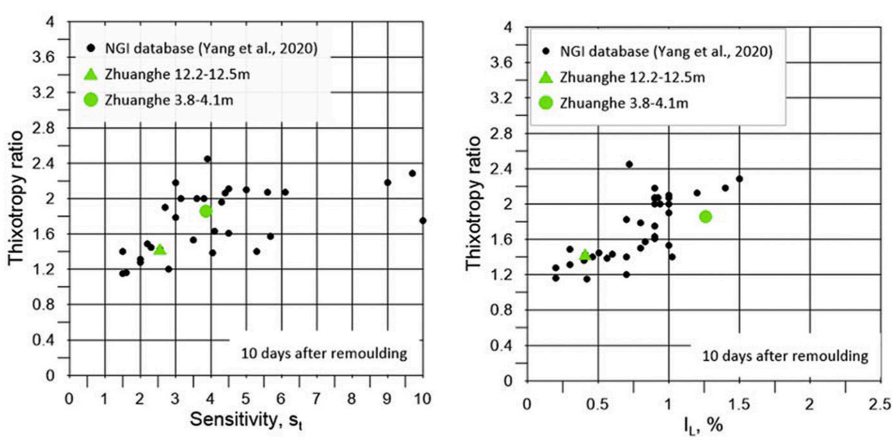


**Fig. 7.** Thixotropy ratio at 10 days after remoulding as a function of sensitivity and liquidity index.

- Values of the preconsolidation pressure, $p_c'$ can be obtained from in situ tests and/or geological considerations.
- When the samples are obviously disturbed so that the re-compression consolidation technique (Bjerrum, 1972) does not produce a representative soil structure.

The procedure is developed for use on mechanically over-consolidated materials, but NGI has found that the SHANSEP principle also works when the clay has an apparent OCR due to ageing (Bjerrum, 1972).

Using the SHANSEP procedure, a relationship is determined between the normalized undrained shear strength, $s_u/\sigma_{vc}'$ and the corresponding laboratory overconsolidation ratio, OCR, by consolidating the test specimens to a stress, $\sigma_v'_{max}$, that is higher than the natural $p_c'$ and unloading different samples to different consolidation stresses. The values, $(s_u/\sigma_{vc}')_{OCR=1}$ and m, in the following equation can be determined numerically or by plotting as shown in Fig. 9.

$s_u/\sigma_{vc}' = (s_u/\sigma_{vc}')_{OCR=1} * (OCR)^m$.

Index parameters and SHANSEP parameters for different sites world wide are given in Yang et al., 2019. In general, m seems to vary between 0.70 and 0.98, while $(s_u/\sigma_{vc}')_{OCR=1}$ generally ranges between 0.27 and 0.35 for triaxial compression mode.

The three CAUC results in Table 3 are included in Fig. 9. Ip is plasticity index of clays. There are not enough tests at different OCR-values to determine the parameters for the different clay units on Zhuanghe exactly, but the following SHANSEP parameters seem to give a reasonable fit for the silty clays at the Zhuanghe site.

$(s_{uC}/\sigma_{vc}')_{OCR=1} = 0.31$ and $m = 0.75$ for triaxial compression strength.

## 6. Cyclic behaviour of silty clay and silty, clayey sand

Cyclic shear strength of soils is an important parameter for foundation design under cyclic loading, and cyclic DSS tests were performed on two of the Zhuanghe soil units, the silty clay and the silty, clayey sand.

The tests were performed with both symmetric and non-symmetric cyclic shear stress, i.e. with and without an average shear stress, $\Delta\tau_a$, during cycling. In case of an average shear stress, $\Delta\tau_a$ was applied undrained. The cyclic loading was applied undrained with a load period of 10 s. The cyclic loading was stopped at 15% average shear strain, 15% cyclic shear strain or at 5000 cycles if no failure occurred earlier.

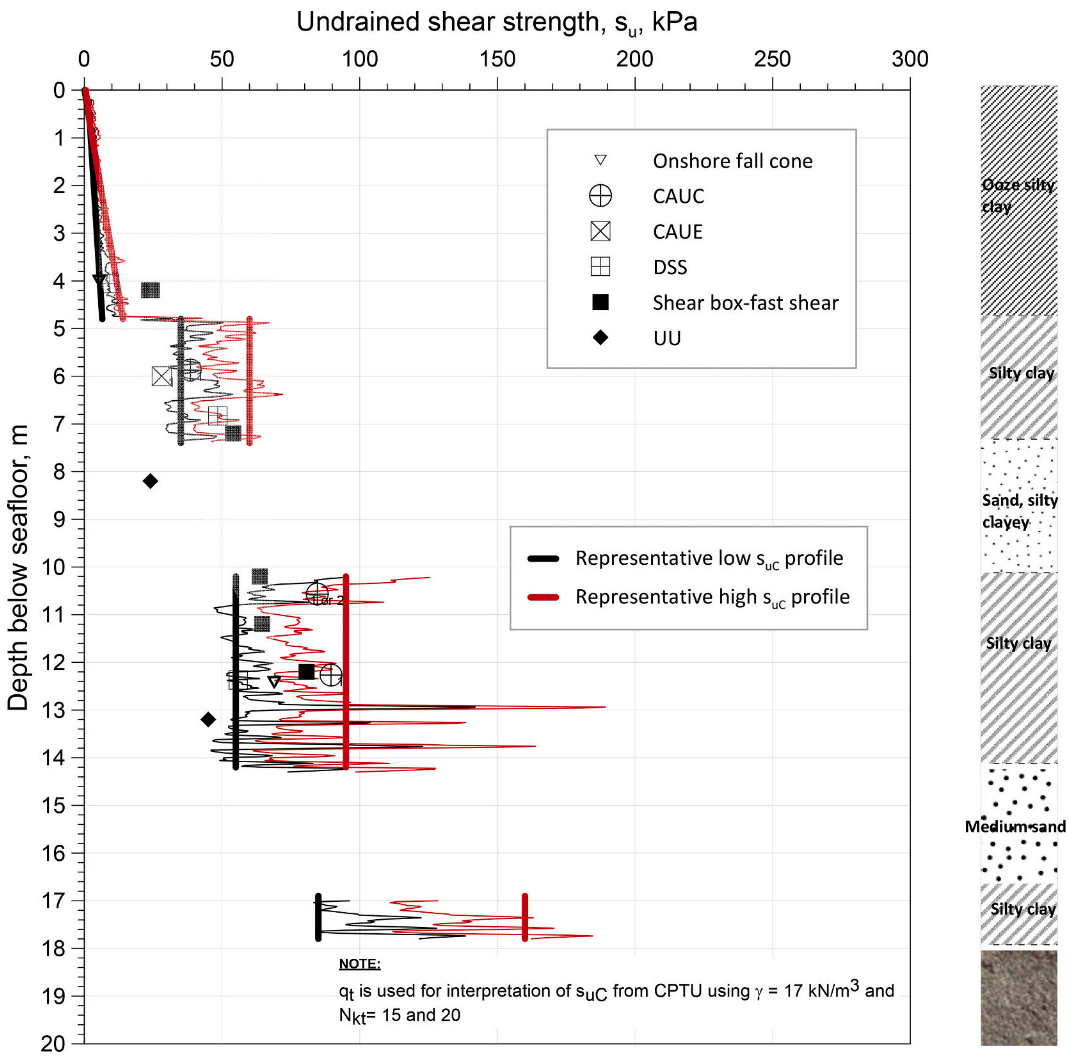


**Fig. 8.** Undrained shear strength at Borehole JT7.

**Table 2**
DSS test results.

| Depth (m) | Water content after consolidation (%) | Plasticity index (%) | Fines content (%) | Vertical consolidation stress, $\sigma_{vc}'$(kPa) | OCR | DSS strength, $s_{uD}$ (kPa) | Strength ratio $s_{uD}/\sigma_{vc}'$ | $G_{max}$ (MPa) |
|---|---|---|---|---|---|---|---|---|
| 4.06 | 49.6 | – | 90.0 | 28.4 | 1.0 | 9.2 | 0.32 | 2.4 |
| 6.83 | 44.1 | 30.0 | 98.6 | 51.6 | 3.0 | 48.5 | 0.94 | 25.3 |
| 8.73 | 25.3 | 10.0 | 38.4 | 70.0 | 4.0 | 89.8 | 1.28 | 75.5 |
| 12.37 | 28.2 | 18.0 | 74.8 | 105.0 | 2.5 | 55.9 | 0.53 | 46.9 |

In general, the results of cyclic DSS and triaxial tests can be summarised in various types of contour diagrams (Andersen, 2015). This includes a failure contour diagram with contours of number of cycles to 15% average or cyclic shear strains as function of cyclic and average shear stresses. Other diagrams give cyclic and average shear strains and permanent pore pressure as functions of number of cycles in one diagram type and as function of cyclic and average shear stresses after different number of cycles in another diagram type (e.g. Andersen, 2015). The contours for clay are typically normalized by a reference static shear strength.

Failure contour diagrams constructed based on the cyclic DSS tests performed on the two Zhuanghe soil units are presented in Fig. 10. For the silty clay unit, the test with $\Delta\tau_a > 0$ that failed after 6.0 cycles does not fit very well with the contours, since more cycles to failure is expected for this test. For the silty, clayey sand unit, the tests with $\Delta\tau_a > 0$ that failed after 4 cycles does not fit very well with the contours either. Both are believed to be due to local variations in the soil. The main properties of the tested soils are given in Table 4.

Left: Silty clay at depth 6.8 to 7.1 m. Right: Silty, clayey sand at depth 8.7 to 9.0 m.

## 7. Shear modulus

Robertson (2009) provided a simplified way to estimate the small strain shear modulus over a wide range of soils using CPTU data. Andrus et al., 2007 developed relationships to estimate shear wave velocity from CPTU measurement. These methods were calibrated to measured shear wave velocity from PCPT tests. The small strain shear modulus at the Zhuanghe site are evaluated by using both methods. The estimated values based on the CPTU at borehole JT7 are given in Fig. 11, including

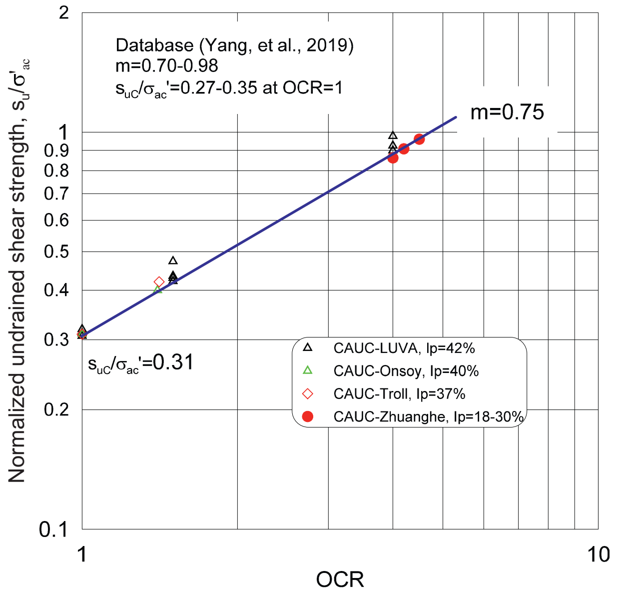


**Fig. 9.** SHANSEP parameters

$G_{max}$ values measured in the NGI laboratory. The $G_{max}$ values were measured in the DSS tests on the silty clay and the silty, clayey sand (Table 2).

Andersen (2015) provided a database relating $G_{max}$ to plasticity index, and the $G_{max}$ values measured in the laboratory on the Zhuanghe samples are compared to the data base in Fig. 12. The $G_{max}$ values of the Zhuanghe samples on silty clay fit well with the database (Fig. 12).

## 8. Conclusions

The paper presents typical soil parameters that can be used for foundation design at the Zhuanghe offshore wind farm site. The undrained triaxial compression shear strength of the normally consolidated ooze clay and the overconsolidated silty clay can be estimated from CPTU tests by using a cone factor of $N_{kt}$ = 15–20. Undrained shear strength of the overconsolidated silty clay layer can also be obtained from SHANSEP parameters that agree with parameters from the literature. Cyclic contour diagrams that can be used for design of wind turbine foundations are developed from laboratory DSS tests. Both Robertson and Andrus methods can be used to evaluate the small strain shear modulus for Zhuanghe soils. Thixotropy strength regain after remoulding is high for the top ooze silty clay compared with the silty clay layer. This difference can be related to the difference in sensitivity and liquidity index and agrees well with the NGI data base. The results show that existing data bases could be used to estimate soil parameters for preliminary design before site specific investigations and laboratory testing are performed.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Table 3**
CAU test results.

| Depth (m) | Water content after consolidation (%) | Plasticity index (%) | Fines content (%) | Vertical consolidation stress, $\sigma_{vc}'$ (kPa) | OCR | $K_0$ | Triaxial strength, $s_{uC}$ (kPa) | Strength ratio $s_{uC}/\sigma_{vc}'$ |
|---|---|---|---|---|---|---|---|---|
| 5.87 | 44.8 | 30.0 | 98.6 | 42.4 | 4.2 | 0.8 | 38.5 (CAUC) | 0.91 |
| 10.57 | 27.9 | 30.0 | – | 88.2 | 4.5 | 0.75 | 84.6 (CAUC) | 0.96 |
| 12.27 | 27.7 | 18.0 | 74.8 | 104.1 | 4.0 | 0.7 | 89.6 (CAUC) | 0.86 |
| 6.00 | 45.0 | 18.0 | 98.6 | 43.7 | 4.0 | 0.8 | 28.1 (CAUE) | 0.64 |

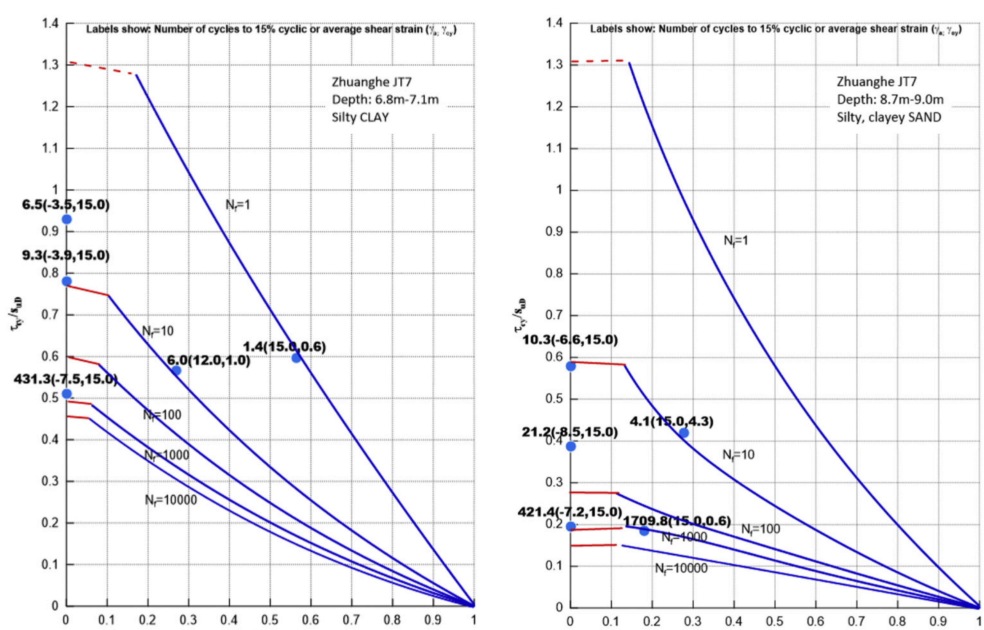


**Fig. 10.** Cyclic failure contours for two soil units at Zhuanghe site.

**Table 4**
Cyclic DSS parameters for the two soil units.

| Soil type | Depth (m) | Water content (%) | Plasticity index (%) | Fines content (%) | Static strength ratio, $s_{uD}/\sigma_{vc}'$ | Cyclic stress to strength ratio, $\tau_{cy}/s_{uD}$, at $\tau_a = 0$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | N = 1 | N = 10 | N = 100 | N = 1000 | N = 10,000 |
| Silty clay | 6.8–7.1 | 44–48 | 30 | 98 | 0.94 | 1.32 | 0.78 | 0.59 | 0.49 | 0.45 |
| Silty, clayey, sand | 8.7–9.0 | 25–27 | 10 | 38 | 1.28 | 1.31 | 0.59 | 0.27 | 0.19 | 0.16 |

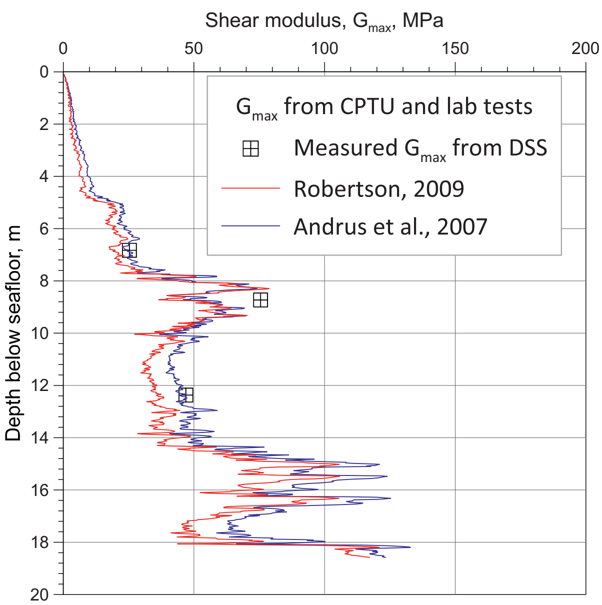


**Fig. 11.** Estimated and measured $G_{max}$.

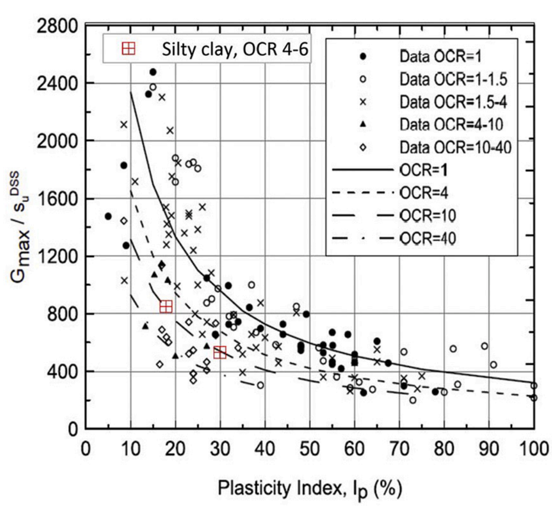


**Fig. 12.** Correlations between normalized shear modulus and plasticity index (data base from Andersen, 2015).

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