Pile-soil Interface Shear Characteristic Research in Offshore Wind Power Project

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Abstract. Considering the difficulties encountered during the evaluation of the pile-soil interface parameters for the offshore wind power project, direct shear test, soil-structure interface shear test and the numerical analyses were carried out. Through these the pile-soil interface characteristics and influencing factors were revealed. Based on the direct shear test and soil-structure interface shear test results, the strength of the soil-structure interface was found to be less than that of the internal strength of the soil, most stress-displacement curves of the interface shear test presented strain softening, where the interface strength decreased after reaching the peak value to a stable residual strength. On the contrary, strain softening was unlikely to be discovered directly on the shear test. The material impacts and roughness on the soil-structure interface and the shear strength was found when a reduction factor was introduced to quantify the shear strength of the soil-structure interface, with a range of 0.53~0.83. Combined with numerical analysis, stress concentration is generated at both the edge and the center of the shearing surface. The shear stress and shear displacement decreased gradually from edge to center of the shearing surface, and the shear displacement was strongly related to the size of the shear fracture.

Key words: Pile-soil interface parameters; Interfacial shear test; strength reduction method

1. Preface

The interface between soil and structure has always been an important research topic in geotechnical engineering. Potyondy used stress and strain controlled direct shear instruments to explore the mechanical properties of the interface between different soils and structural building materials [1]. Hu Liming et al. carried out the interface shear test between sand and steel plates by using an improved strain-controlled direct shear instrument, and explored the influence of different steel plate surfaces’ roughness on the interface mechanical properties [2-3]. Clough et al. studied the mechanical properties of the soil-concrete interface by direct shear test, and the τ-δ curve of the interface showed a hyperbolic relationship [4]. Pineda-Jaimes et al. used direct shear boxes to realize the soft clay-concrete interface with different roughness, then measured and studied the interface peak value and residual shear strength [5]. Evgin and Fakharian used a self-developed cyclic three-dimensional contact surface single shear instrument to carry out multidimensional shear tests in soil-steel and steel-steel interfaces under normal boundary conditions of constant stress and constant stiffness. The effects
of different stress paths on the interfacial $\tau$-$\delta$ relationship and shear strength were also investigated [6-8]. In view of the difficulties in the geotechnical design of offshore wind power foundations, direct shear test of pile-soil interaction interface, direct shear test of soil samples and interface shear test of soil-structure were carried out and documented in this paper.

2. Geotechnical Direct Shear Test Results

2.1 Test Plan

Soil samples with water content of 21% were prepared from clay materials, and the dry density of soil samples was set as 1.68g/cm3. The soil samples were put into the shear box with the vertical pressure set at 100, 200, 300 and 400kPa respectively. The consolidation fast shear test was carried out at the shear rate of 1.2mm/min. The test was stopped when the reading of the force measuring ring was unchanged or the test began to decrease. Test results as shown in Fig. 1.

![Figure 1. Direct shear deformation test and diagram of soil samples](image)

2.2 Test Results

The test data are drawn as stress displacement curves. Generally, the shear displacement or relative shear displacement are used as the abscissa. The relative shear displacement describes the real shear displacement of soil samples, so the shear stress and relative shear displacement are used to describe the shear process of soil. The shear stress-relative shear displacement ($\tau$-$\omega$) curve of direct shear test of soil samples under different vertical pressures was drawn, as shown in Fig. 2. The shear stress-displacement curve conformed to the hyperbolic model, and the shear strength approached a stable value without a peak value with the increase of the relative shear displacement, showing the strain hardening characteristic. The maximum shear stress under each vertical pressure was selected as the

![Figure 2. Direct shear $\tau$-$\omega$ relation curve and shear strength relation curve](image)
shear strength. As shown in Figure 1, the cohesion of clay is \(C = 71.6\text{kPa}\) and the internal friction angle \(\phi = 11.5^\circ\).

Direct shear apparatus has simple structure, convenient operation, the advantages of rapid test, but there are edge stress concentration, shear plane shrinking eccentric load, axial force, side pressure caused by the vertical faults, such as the loss of soil drainage condition is difficult to control strictly, in order to better simulate the actual engineering, need to be constantly improved and perfected.

3. Interface Shear Test

3.1 Test Plan

| Project                  | Test content                          |
|--------------------------|---------------------------------------|
| Roughness contrast       | Smooth steel-soil interface           |
| Material contrast        | Rough steel-soil interface            |
|                         | Smooth steel-soil interface           |
|                         | Nylon-soil interface                  |

The interaction relationship between pile-soil interface and its influencing factors were studied. A strain controlled direct shear apparatus was used to compare steel and nylon materials. The soil sample was consistent with the direct shear test, and the sample size was 20mm high, the diameter was 61.8mm. Smooth steel surfaces and rough steel surfaces were selected for the steel sample. The average gradient of roughness of the smooth and rough steel surface was 6.3-12.5μm and 200-300μm respectively, and the roughness of nylon was 6.3-12.5μm. The test scheme is shown in Table 1.

The vertical pressure was 100, 200, 300, 400kPa with shear velocity at 1.2 mm/min. The shear stress relative displacement \((\tau - \omega)\) curve was then drawn. The shear stress-relative displacement curves and shear strength curves of the interfacial shear tests were measured under each vertical pressure listed, and the friction coefficient of the interface was obtained by linear regression analysis.

3.2 Test Results

3.2.1 Smooth Steel-Soil Interface

![Figure 3. \(\tau - \omega\) relation curve of smooth steel-soil interface and interfacial shear strength relation curve](image)

The shear stress-relative displacement curve of the interface is shown in Figure 3. It demonstrates that there were obvious differences with the results of direct shear. At the beginning, the interfacial shear stress increased linearly with the change of displacement, and finally approached a stable, constant value. The interfacial shear stress-relative displacement shows us there was strain hardening characteristics. The slope of the growing section in the \(\tau - \omega\) relation curve of different pressures was shown to be near identical. When the relative slip was between 0.1mm and 0.3mm, the shear stress of
the interface reached the peak, and the curve no longer conforms to the hyperbolic model. With the increase of vertical pressure, the shear strength and relative shear displacement of soil samples continued to increase. The interface strength index: cohesion $C = 22.5$ kPa, interface friction Angle $\phi = 10.7^\circ$, relative to the soil shear strength index decreased significantly.

### 3.2.2 Rough Steel-Soil Interface

The maximum shear stress of the interface increased with an increase in the vertical pressure. The relative shear displacement corresponding to the peak shear stress also increased (Figure 4) with a similar curve to that of the smooth steel-soil interface. However, when the $\tau$-$\omega$ curve of the interface between rough steel and soil reached the peak value, the strength decreases with the increase of shear displacement, and finally reached a stable value. It was found that the peak value and residual value of the interface shear strength exist. When the pile-soil interface was rough, the soil near the interface formed a shear band, and the soil usually showed strain softening and shear dilatancy. When the pile-soil interface was smooth, the sliding failure occurred along the pile-soil interface, which can be shown as strain hardening.

![Figure 4. $\tau$-$\omega$ relation curve and shear strength relation curve of the interface between rough steel-soil](image)

The peak value of shear stress was taken as the peak shear strength, and the stable value of shear stress taken as the residual strength. The relationship curve of shear strength is shown in Figure 2-2. The peak cohesion $C$ found was 42.0 kPa, and the peak interface friction Angle $\phi$ was 13.7°. The residual cohesion $C$ was 27.5 kPa, and the peak interfacial friction Angle $\phi$ was 14.0°. The cohesion of residual strength was smaller than that of peak strength, and the friction Angle was basically the same as that of peak strength.

### 3.2.3 Nylon-Soil Interface
Figure 5. $\tau$-\(\omega\) relation curve and shear strength relation curve of nylon-soil interface

The shear stress-relative displacement curve of the nylon-soil interface shear test is displayed in Figure 5. The properties of $\tau$-\(\omega\) relation curve were shown to be close to those of the smooth steel-soil interface. Initially, the shear stress and the relative displacement increased linearly, and the slope of the curve is seen to be basically the same under different vertical pressures. Further on, the shear stress remains basically unchanged, showing obvious strain-hardening characteristics. Strength index of nylon-soil interface: cohesion $C = 25.3$ kPa, and interface friction Angle $\phi = 9.3^\circ$. Due to the matric suction of unsaturated soil, the interfacial cohesion was smaller than that of clay and the friction coefficient was also smaller than that of clay.

4. Analysis of Interface Test Results

The study now will contrast the direct shear test with interface shear test (Figure 6). The shear strength of the rough steel-soil interface was shown to be greater than that of the smooth steel-soil interface, which indicates that lateral resistance can be effectively improved through increasing the roughness in the pile-soil interface.

Figure 6. The relation curve of shear strength and $\tau$-\(\omega\)

The shear strength of the nylon-soil interface was demonstrated to be slightly lower than that of the smooth steel-soil interface, and the average roughness of the smooth steel surface is essentially the same as that of nylon. Compared with the influence of roughness, the influence of material can be ignored. At a vertical pressure of 400 kPa, the test data of different interface shear and direct shear of soil samples were plotted together and compared (Figure 3-1). When the shear stress is low, the curve of interfacial shear test shows a trend of linear increase, and when the shear stress reaches a certain degree, the relative shear stiffness decreases continuously. When the interface is smooth, the $\tau$-\(\omega\) relation curve has the characteristics of an ideal linear elastoplastic and the entailed softening. In the initial stage, the shear stiffness decreases with the relative displacement, and the $\tau$-\(\omega\) relation curve shows hardening.

| Material                              | Vertical pressure(kPa) |
|---------------------------------------|------------------------|
|                                       | 100    | 200    | 300    | 400    |
| Clay                                  | 100    |        |        |        |
| Smooth steel-soil interface           | 92.2   | 112.9  | 131.1  | 154.1  |
| Rough steel-soil interface            | Peak   | 40.9   | 59.8   | 82.1   | 96.6   |
| Residual                              | 65.0   | 92.0   | 117.2  | 138.0  |
| Material                        | Vertical pressure(kPa) | Average |
|--------------------------------|------------------------|---------|
| Smooth steel-soil interface    |                        |         |
|                                | 100                    | 0.44    | 0.53 | 0.63 | 0.63 | 0.56 |
| Rough steel-soil interface     | Peak                   | 0.70    | 0.81 | 0.89 | 0.90 | 0.83 |
|                                | Residual               | 0.56    | 0.68 | 0.82 | 0.81 | 0.72 |
| Nylon-soil interface           |                        | 0.45    | 0.51 | 0.58 | 0.58 | 0.53 |

**Table 3. Interface Strength Reduction Coefficient**

By comparing the shear strength of the direct shear test and the interfacial shear test (Table 2), the interfacial shear strength under the same vertical pressure is generally lower than that of the soil, and the shear failure usually occurs at the interface. In the simulation of pile-soil interface, a virtual thickness elastoplastic interface element considering strength and stiffness reduction is recommended. Table 3 shows the recommended value of the interface strength reduction coefficient obtained from the direct shear interface characteristic test.

5. Numerical Simulation Analysis

5.1 Direct Shear Simulation Analysis

The finite element method was used for numerical simulation, and the Mohr—Coulomb criterion was selected as the constitutive model of soil. The material parameters were shown in Table 4. The soil model adopted spatial tetrahedron design for grid division as shown in Figure 7. Constraints were added to the side and bottom surfaces. A uniform load was added to the surface of 400kPa, forced displacement in the X direction was added to the side below the soil sample, and the maximum shear displacement was 6mm, for calculation and analysis purposes.

| Item    | E/MPa | \(\mu\) | c/kPa | \(\phi/^{\circ}\) | Constitutive model   |
|---------|-------|---------|-------|---------------|---------------------|
| Soil    | 10    | 0.43    | 42    | 13.7          | Mohr—Coulomb        |
Figure 7. Diagram of Grid Division

Figure 8. Stress Nephogram and Maximum Shear Stress Nephogram of Shear Plane

The simulation results are shown in Figure 8. The stress was shown to be mainly concentrated on the edge of the shear plane, and the shear plane stress nephogram was symmetrically distributed along the center of the soil sample. During the shear process, the shear stress of soil was distributed homogeneously on the shear plane, while the shear stress decreased gradually from the edge of the shear plane to the center of the shear plane.

5.2 Interfacial Shear Simulation Analysis

During the shear process of pile-soil interface, the nonlinear characteristics of pile-soil interface failure zone were particularly obvious. The soil constitutive model was a Mohr—Coulomb model, and the steel was linear elastic material. The model material parameters are shown in Table 5. The steel-soil interface parameters were reduced according to the soil shear strength index, and the reduction coefficient was set as 0.815.

| Item   | E/MPa | μ   | c/kPa | φ/°   | Constitutive model         |
|--------|-------|-----|-------|-------|----------------------------|
| Soil   | 10    | 0.43| 42    | 13.7  | Mohr—Coulomb               |
| Steel  | 210000| 0.30| —     | —     | Elastic model               |

Constraints were placed in different directions on the side and bottom surfaces of soil and steel samples, as shown in Figure 9. In the pile-soil interface shear test, the stress concentration occurred at the edge of the shear plane. Results differed from the soil shear, as the stress in the X direction of the interface was asymmetrical. The steel interface was dominated by tensile stress, and the pile-soil interface in the center was found to interact with each other, resulting in greater stress.
As shown in Figure 10. Shear stress nephograms with displacements of 3mm, 6mm and 9mm were selected for comparative analysis. The maximum interfacial shear stress of the sample appeared on the left side of the shear plane. It can be seen that the shear failure of the interface may start from the inside of the shear plane, and the relative shear displacement can occur at all positions. By comparing Figure a, b and c, it was found that the shear stress gradually increased with the increase of shear displacement, and the stress concentration at the edge and center was more obvious.

The vertical and Y-axis sections of the soil samples were made to obtain the displacement nephogram of the section (Figure 10. d). The displacement of the pile-soil interface was consistent, and the shear displacement of the soil sample varied along the direction of the vertical shear plane. Under the effects of the surface boundary conditions and the cohesion of steel interface, the internal displacement of soil samples was larger in the central area and smaller at both ends, while the pile-soil interface had a certain specified thickness. Compared with the soil direct shear test and the interface shear test, it was found that the displacement and stress-strain relationship between the two are different due to the different material properties of the contact surface, and the shear displacement is closely related to the size of the shear joint.

6. Conclusion
(1) The interfacial strength obtained from the interfacial shear test is less than the soil strength itself, and the stress-displacement curve of the interface often shows softening phenomenon, that is, to achieve the peak of the interfacial strength and then decays and tends to become stable, while the soil itself does not necessarily undergo strain softening.

(2) The interfacial strength reduction coefficient can be determined by direct shear and interfacial shear tests of soil samples, and the interfacial strength reduction coefficient ranges from 0.53 to 0.83 for different materials.

(3) Stress concentration occurs at the edge and the center of the soil on the shear plane, the shear stress and shear displacement gradually decrease from the edge of the shear plane to the center. Moreover, the shear displacement is closely related to the size of the shear joint. The interfacial shear test on conventional direct shear instrument cannot reveal the real interfacial deformation law.

7. Discussion

(1) Based on the direct shear and interfacial shear tests of soil samples, the number of test samples can be increased and not limited to the material type studied in this paper. Interfacial strength tests and interfacial strength reduction coefficient studies can be carried out for a variety of materials.

(2) The stress and displacement curves of the interfacial shear test almost have softening phenomenon. Further researches could be carried out in the future on different soil samples to determine whether the soil samples have strain softening of internal shearing failure.

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