The Degenerate Mechanism of Sand-Concrete Interface under Cyclic Loading

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ABSTRACT: The sliding interaction between the sand and the surface of the structure is involved in many aspects of geotechnical engineering and is particularly important for the derivation of the shaft capacity of piles. A constant normal stiffness direct shear apparatus is designed and applied herein to research the soil-structure interface weakening mechanism under cyclic loading. The test results show that the sand-concrete shear stress and normal stress change in the “Hysteresis loop” and “Butterfly” trends with shear displacement respectively in a complete shear cycle. The difference of adjacent "Hysteresis loop" or "Butterfly" is evident in the initial stage of cyclic shear, but tends to gentle after 15 cycles. The evident decays of both the shear stress and the maximum normal stress take place during cyclic shearing, which is approximately logarithmically with the shear cycles. The shear strength of the interface is approximately linear with the normal stress under different cycles. The percentage of particle breakage is between 5.5% and 6% of the original sand after 20 shearing cycles. The percentage of particle breakage and the degeneration rate of shear stress and normal stress increase with the increase of the initial normal stress and the amplitude of shear displacement.

KEYWORDS: sand-concrete interface; cyclic loading; the initial normal stress; the amplitude of shear displacement; degenerate effects; particle breakage

INTRODUCTION

The research of the interactions between buildings and soils is significant in civil engineering and geotechnical research. With the increasing application of pile foundation, the pile-soil interface shear issue is common in geotechnical engineering. The mechanical properties of the interface have an important effect on the deformations and interactions of pile-soil. Scholars attach great importance to the study of interface mechanics.

Since Potyondy conducted tests to perform mechanical of the interface between soil and structure by using a direct shear apparatus, it has become a hot spot in the geotechnical engineering. Clough et al. researched the mechanical properties of soil and concrete interface by the direct shear test, which revealed the hyperbolic curve between the shear stress and the relative shear
displacement. Brandt et al. studied the contact issues between soil and concrete with a large direct shear apparatus. It was found that soil near the interface occurred progressive failure, which affected the stress-strain relationship. HU Li-ming et al. conducted the shear test with the different interface roughness between sand and structure by using improved strain control type direct shear apparatus. Many scholars conducted shear tests between soil and structural surface, which revealed the relationship between the mechanical properties and normal stress, shear rate, shear displacement as well as the structural roughness (Zhou Guo-qing et al., Liu Xi-liang et al., Liang Yue et al.).

PHC pipe pile has become one of the main pipe types in the geotechnical engineering. But the existing theoretical results still cannot fully reveal the shear fatigue between pile and soil. In order to fully understanding the interface circulation weakening mechanism, a comprehensive research program was conducted to reveal the influence of different shear displacement and initial normal stresses. This study was carried out by self-developed large-scale constant normal stiffness interface circulating shear apparatus.

1 THE DEVELOPMENT MECHANISM OF CNS AND CNS SHEAR APPARATUS

According to the disturbance extent of soil during the pile driving, White et al. divided the soil sample area into regions: shear zone, elastic zone and undisturbed zone, as shown in Fig. 1. In the shear zone, there exists a specific thin shear zone, where the soil adjoins the pile shaft. Within the scope of the shear zone, the soil particle occurred shear failure. The soil particles are broken into small particles, and soil particle size which is middle previously becomes smaller. The undisturbed zone soil does not undergo any deformation, because the soil is far away from the pile. The soil in the elastic zone is located between shear zone and undisturbed zone, which mainly occurs horizontal elastic deformation.

Based on above, the characteristics of pile-soil interface and the deformation characteristics of soil are simulated by CNS constant stiffness shear test. Shear plane can simulate the shear action between pile and soil. The spring loading can simulate the shear action of soil in the elastic zone. And the deformation of spring $\Delta t$ indicates the variation of shear zone thickness.

The variation of shear zone thickness $\Delta t$ can lead to the variation of pile lateral normal stress $\Delta \sigma_n$, and the relationship is expressed in Equation (1):

$$\Delta \sigma_n = \frac{4G}{D} \Delta t = k \cdot \Delta t.$$

In which, the parameter $G$ denotes shear modulus of soil around the pile. The parameter $k$ denotes the stiffness of the spring. The parameter $D$ denotes the pile diameter.

The constant normal stiffness direct shear apparatus used in this research is shown in Fig. 2. The shear box of the shear apparatus is a "U" groove. The interior (placing concrete) dimension of shear box is 500 mm x 300 mm x 100 mm (length x wide x height). The interior dimension of upper shear box is 700 mm x 300 mm x 300 mm (length x width x height). Constant normal stiffness is provided by spring, and the stiffness $k$ is 50 kPa/mm. In the shearing process, the shear area is constant. Fiber Bragg Gratings Strain Sensors were embedded in the surface of concrete specimen, which measuring the shear stress of pile-soil interface.
2 EXPERIMENTAL MATERIALS

2.1 STANDARD SAND

The test used dry ISO standard sand, its median diameter is 0.34mm. The relative density of the standard sand is 2.71. The maximum and minimum porosity ratios are respectively 0.856 and 0.402. And the particle sizes range from 0.1mm to 1.0mm, the friction angle of sand is 40.4°.

2.2 CONCRETE SPECIMEN

The dimensions of Concrete specimen are 500 mm×300 mm×100 mm (length × wide × height), and the strength grade is C40. The mixing ratio is 2:4.08:7.82:1 (cement: sand: gravel: water). The surface of concrete specimen was polished with a grinding wheel, as shown in Fig. 3.

3 TESTING PROGRAM

Fig. 4 shows the schematic view of cyclic shear paths. The x-axis represents the relative shear displacement of the pile-soil interface, and, a complete shear cycle consists of four phases (①→②→③→④). The positive direction of the x-axis is defined as forward loading. The loading phase consists of phases ① and ③, and the unloading phase includes phases ② and ④.

Four groups of constant stiffness cycle shear tests were carried out, involving two variables of the initial normal stress and the amplitude of shear displacement. Each test included 20 cycles. The specific cyclic shear testing program is shown in Tab. 1.

<table>
<thead>
<tr>
<th>Test code</th>
<th>Shear rate/(mm/min)</th>
<th>Initial normal stress/ kPa</th>
<th>Amplitude of shear displacement/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-1</td>
<td>5</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>CS-2</td>
<td>5</td>
<td>110</td>
<td>10</td>
</tr>
<tr>
<td>CS-3</td>
<td>5</td>
<td>90</td>
<td>5</td>
</tr>
<tr>
<td>CS-4</td>
<td>5</td>
<td>110</td>
<td>5</td>
</tr>
</tbody>
</table>
4 TEST RESULTS

4.1 SHEAR STRESS-DISPLACEMENT BEHAVIOR WITH DIFFERENT CYCLE HISTORY

The shear stress-shear displacement curves of the 4 groups of constant shear tests are shown in Figure 5. The phase of the cyclic shear test is monotonic straight shear test. It can be seen that the shear stress-shear displacement curves of concrete-sand interface under different initial normal stress and shear displacement amplitude show similar trends. The shear stress increases with the increase of shear displacement increase in the initial stage, and decreases after the shear stress reach the peak, but it becomes gentle when deceases to a certain value. This phenomenon is shear softening. It is shown that the initial normal stress and the shear displacement do not have an essential effect on the shear stress of the monotone straight shear test interface. As the initial normal stress and shear displacement amplitude increase, the peak shear stress increases slightly.

The shear stress and shear displacement curves of the interface are basically closed in a complete shear cycle, showing the development of hysteresis loop. With the increase of the number of cycles, the slope of the loading section of the shear stress displacement curve increases gradually and is close to the slope of the unloading section. There are some differences in the relationship between the shear stress and the relative displacement of the same cycle in different shear directions. The friction angle of initial shear direction is slightly lower than that in the reverse direction, and the slope of the unloading section is slightly larger. This is consistent with the conclusion of Zhang Ga et al. With the increase of the number of cycles, the hysteresis loop tends to be "flat". At the initial stage of the cyclic shear, the adjacent hysteresis loops are quite different and tend to coincide with the increase of the number of cycles. It is shown that the interface shear stress is weakened with the increase of the number of cycles, with most of the reduction occurring in the initial stage. This is mainly due to the reduction of soil volume during shearing. It is concluded that the reduction of soil is mainly due to the rearrangement and fragmentation of particles. The long axis and the minor axis of the particles are chaotic in the original state. In the initial shear, the soil particles in the vicinity of the structural plane slip, rotation and other mesoscopic changes. Meanwhile the longitudinal direction of the particles is biased towards the initial shear direction. The soil particles at the high potential are lowered to a lower potential state and small particles into the gap between the large particles. The above reasons all reduce the volume space occupied by soil particles. Particle crushing is another important reason for the reduction of soil, some of the large particles are broken into small particles, and the newly formed small particles enter the voids of large particles. Both the rearrangement of particles and the breakage of large particles are more obvious at the initial shear stage, so the weakening of shear stress mainly occurs in the initial stage. The difference of adjacent "Hysteresis loop" is evident in the initial stage of cyclic shear, but tends to gentle after 15 cycles. It can also be found that the rate of degeneration of the shear stress increases as the initial normal stress and shear displacement increase. The shear stress decreases rapidly from the minimum positive value to the maximum negative value. The process undergoes a smaller shear displacement. After a smooth segment, the minimum negative value increases rapidly to the maximum positive value. This is consistent with the finding of Giuseppe Moetara.
4.2 NORMAL STRESS-DISPLACEMENT BEHAVIOR WITH DIFFERENT CYCLE HISTORY

The normal stress-shear displacement relationship of the four groups of constant stiffness shear tests is shown in Figure 6. It is clear that normal stress-shear displacement curves of the concrete-standard sand interface are in a "butterfly" developing tendency. "Butterfly" presents a downward trend and tends to be "flat", in the initial stage of cyclic shear. The difference of adjacent "Hysteresis loop" or "Butterfly" is evident in the initial stage of cyclic shear, but tends to gentle after 15 cycles. It is shown that the normal stress of the interface decreases with the increase of the number of cycles, and the weakening is mainly concentrated in the initial stage. The degeneration rate of normal stress increases with the increase of initial normal stress and shear displacement. Dakuo von also conducted such a study, and the research conclusion is similar to this. The degeneration of the normal stress is another important reason for degeneration of the shear stress.
4.3 VARIATIONS OF MAXIMUM SHEAR STRESS AND NORMAL STRESS WITH CYCLE HISTORY

Figure 7 shows variations of shear stress or normal stress with cycle history. It can be seen that with the increase of the number of cyclic shear, the shear stress and the normal stress are obviously weakened and weakened mainly in the first 5 cycles. With the increase of the number of cycles, the shear stress decreases and the normal stress weakening rate decreases and tends to be gentle. This is consistent with the findings of Liu Junwei et al. and David W. Airey et al. After 20 cycles of shear stress, the normal stress is reduced by about 50%. The fitting results are also shown in Fig. 7, and the fitting functions are shown in equations (2) and (3):

\[ \sigma = a - b \ln(N - c), \]  
\[ \tau = m - n \ln(N - l). \]

Where, \( a, b, c, m, n, l \) are constants, the values of \( a \) and \( m \) are related to the initial normal stress, \( b \) and \( n \) are related to the rate of weakening; \( N \) is the number of cycles.

Figure 6. Curves of normal stress and shear displacement behavior with different cycle history.

Figure 7. Variations of shear stress or normal stress with cycle history.
The evident decays of both the shear stress and the maximum normal stress take place during cyclic shearing, which is approximately logarithmically with the shear cycles. It is roughly shown that the degeneration rates of shear stress and normal stress increase with the increase of the initial normal stress and the shear displacement.

4.4 STRENGTH CHARACTERISTIC

Fig. 8 shows stress path of concrete-standard sand interface. As can be seen from Figs. 8a and 8b, the stress path of the interface under different initial normal stresses is similar. With the increase of the cyclic number, sand sample volume reduce continually and the normal stress is decreasing, which lead to the degeneration of shear stress. The shear stress of interface reaches the strength envelope at first cycle, until the interface is destroyed. The main phenomena is the strain softening of the pile-soil interface, that is, the structural crushing of the sand particles and the surface grinding of the concrete broken. It can be seen that the interface friction angle of CS-1 and CS-2 are about 31° and 32° by eq. \( \tan \phi = \tau / \sigma \). The shear strength envelope of the pile-soil interface is close to the straight line at cycle 5, 15, 20. This means that the shear strength of the pile-soil interface is linearly related to the normal stress, which is similar to the result of Zhang Ga. The interfacial friction angle between the concrete and the standard sand reaches approximately 27° and 28° in Figs. 8a, 8b, respectively. And angle attenuation drops to 12.9%, 12.5%, respectively.

![Figures showing stress path](image)

**Figure 8. Curves of stress path with cycle history.**

As observed in Figs. 8c and 8d, the shear stress of interface do not reach the strength envelope at first cycle when the amplitude of shear displacement is 5mm. This is similar to conclusion of Feng Dakuo. The main reason is that the sand density of the test is about 90%, which belongs to the dense sand. The pile-soil interface shows dilatancy behavior under the coupling of various test conditions. The shear strength of the pile-soil interface is also linearly related to the normal stress. Meanwhile, interface friction angle of CS-3, CS-4 test is 34°, 35°, respectively.
4.5 PARTICLE BREAKAGE

After the cyclic shearing, the particle gradation of sand samples was measured at 150 g per 1 cm at a distance of 5 cm from the pile-soil interface height. Grading curves of sand are plotted in Fig. 9. It is clear that only the soil particles in the range of 1 cm adjacent to the pile-soil interface are seriously damaged. The median particle diameter is 0.18 mm, 0.16 mm, 0.19 mm, 0.17 mm in the range of 0-1 cm from the interface in the test CS-1, CS-2, CS-3, CS-4, respectively. And they are smaller than the median diameter of the original sand.

The parameter $B$ is called total percentage of particle breakage and given by Equation (4).

$$B = \int_{0.1}^{0.1} \frac{1}{y_0} \int_{y_0}^{y_0-1} dy$$

In which, the original values of $y_0$; the $y_0-1$=the values of after loading.

Particle breakage occurred mainly in the range of 0-1 cm from the pile-soil interface. According to the formula, percentage of particle breakage of the four groups is 5.6%, 6.0%, 5.5%, 5.8%, respectively. The percentage of particle breakage after 20 shearing cycles is between 5.5% and 6% of the original sand. And this ratio increases with the increasing initial normal stress and shear displacement.

5 CONCLUSIONS

In order to fully understanding the interface circulation weakening mechanism, a comprehensive research program was conducted to reveal the influence of different shear displacement amplitudes and initial normal stresses. This study was carried out by self-developed large-scale constant normal stiffness interface circulating shear apparatus. The main conclusions are as follows:
(1) The curves of the shear stress and shear displacement on the interface are basically closed in a complete shear cycle, showing the development of hysteresis loop. The normal stress-shear displacement curves are in a "butterfly" developing tendency. The difference of adjacent "Hysteresis loop" or "Butterfly" is evident in the initial stage of cyclic shear, but tends to gentle after 15 cycles.

(2) The evident decays of both the shear stress and the maximum normal stress take place during cyclic shearing, which is approximately logarithmically with the shear cycles. The degeneration rate gradually becomes smaller and tends to be gentle. The degeneration rates of shear stress and normal stress increase with the increase of the initial normal stress and the shear displacement amplitude. The shear strength of the interface is approximately linear with the normal stress in different cycles.

(3) The soil particles in the range of 1 cm adjacent to the pile-soil interface are seriously damaged. Particle breakage occurred mainly in the range of 0~1 cm from the pile-soil interface. The percentage of particle breakage is between 5.5% and 6% of the original sand after 20 shearing cycles. The breaking rate of the particles increases with the increase of the initial normal stress and the amplitude of shear displacement.

(4) During cyclic shearing, the degeneration of the shear stress and the normal stress arise mainly from the reduction of soil volume, which due to the shear crushing and the rearrangement of the particles in the pile-soil interface.

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