Research on Change Laws of Pore Water Pressure of Soft Clay in the Large-scale Wave Flume

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Abstract: The study on the interaction between wave structure and soft clay foundation is carried out in the large scale wave flume trough of the Academy of communications and transportation under the construction of the research on the failure mechanism and design parameters of the port hydraulic structure under the harsh hydrology condition. The remolding technology of the soft clay foundation of the Yangtze River mouth is studied. The model test scale of is 1:5. In the test, the strength of the original soil can be reduced to the similarity of the test phenomenon. The soil strength is reduced by increasing the water content of the original soil, and a series of tests are made on the characteristics of the original soil. The strength of soil increases with the increase of static time. The early growth is fast and the later growth is slow. In the experiment, the soil pressure and pore water pressure sensor were arranged to observe the change rule of soil pressure and pore water pressure under the action of wave. By arranging water pressure sensor and laser displacement sensor, the force and settlement of the structure of the semicircle caisson were observed. In this paper, the variation rule of earth pressure and pore water pressure under different wave heights and longtime waves are studied. The pore pressure and soil pressure change with the wave action, the influence of pore pressure increases with the increase of wave height. Maximum pore pressure occurs at a certain depth of soil. The change in pore pressure is irregular. After a certain value is reached, the soil is softened and destroyed.

1. Introduction

Tianjin Research Institute for Water Transport Engineering, M.O.T. established 1 set of large scale wave test flume (large flume for short) in July 2014. The designed total length, width and largest depth of the large flume are 450m, 5m and 12m respectively. The large flume test section is reserved with the sand tank, and the test of interaction among wave-structure-soil foundation can be conducted. The sand tank is 100m long, the sand layer thickness is 4m, and the distance from the sand tank top to the flume top is 8m. Relying on Research on Damage Mechanism of Port Hydraulic Structures at the Harsh Hydrological Conditions and Optimization of Design Parameters for the construction science and technology project of Ministry of Transport, the test of interaction among wave-structure-soft clay foundation is conducted in the large scale wave flume.
For the problem of changes in mechanical properties of the foundation soil under action of the reciprocating load, many research findings have been accumulated at home and aboard. Many damages to the soft soil foundation are caused due to soil weakening after action of cyclic load. The strength of the soft clay foundation soil may be reduced under action of the wave power, so as to endanger stability of the port engineering structure. It arouses people’s attention internationally, and many theoretical and experimental researches have been conducted\[3\]-[7]. Xiao Zhong adopts Lanczos method for modal analysis of interaction between the cylindrical caisson foundation breakwater structure and the foundation. Jiang Minmin researches the problem of interaction between the complicated breakwater structure and the soft ground under action of wave load. In 1991, Yamazaki, Shan Qongqi et al. from Japan conducted dynamic triaxial test of the soft clay sample, and explore attenuation law of strength and deformation modulus of soft clay under action of the reciprocating load. Port and Harbor Research Institute of Ministry of Transport, Japan systematically researches various liquefaction phenomena during hydraulic reclamation of cohesive soil foundation and fine sand foundation under wave action. Especially indoor model test related with wave and foundation. The strength of foundation soil may be reduced under action of the wave power, so as to endanger stability of the maritime hydraulic structure.

Fan Qijin et al. conducted Research on Softening Action of Wave on Foundation Soil and Engineering Measures during Deep Water Channel Regulation Project at Changjiang Estuary in 2005. it clearly reveals that there is severe decrease in strength of the near-surface soft clay under action of repeated load of wave (softening), which is the main reason for failure in site foundation stability and sudden sinking of structure.

Geotechnical experiment and large scale wave flume experiment are utilized in the paper for generalized simulation and recapitulation of the form of failure of a training jetty structure and foundation soil at the wave conditions during deep water channel regulation project at Changjiang Estuary. The key is to research the failure form and mechanism of bearing capacity of soft ground under action of wave cyclic load. The engineering example verification experiment is taken as the foundation for the next large scale wave flume experiment and mathematical model experiment, and foundation soil simulation technology and theory are further improved.

2. Overview of the test
The length of a semi-circular body in the prototype of training jetty at Changjiang Estuary is 19.94m. According to the existing research findings, the scope of influence of dynamic load of wave on the existing foundation is about 10m. The width of the large flume is 5m, and the deep groove of simulated foundation is 4m high. Considering influence of bottom boundary of the large flume on the test, the model is designed according to gravity similarity. Through comprehensive consideration of these factors, the model scale is selected as 1:5\[8]. The width of the model caisson is 4.8m, and the gap of 10cm is reserved at both ends and the side wall of the flume.

The semi-circular caisson is made of 1cm thick steel plate. According to the geometric scale, the model of the steel caisson is 1.7m high and 2.84m wide. There is difference between the action between the semi-circular body made of steel plate and the bedding and the prototype concrete material.
3. Preparation for test

3.1 Remodeling of the soft clay

Soil is the anisotropic material, which has the features of granularity, diversity and natural variability. Therefore, only approximate similarity of the bearing capacity is satisfied during the model test, i.e., determine that soil strength satisfied test requirements.

For determination of the foundation soil strength, calculate the bearing capacity of the prototype foundation according to the engineering data of Changjiang Estuary, calculate the model foundation bearing capacity according to the scale of 1:5, and then conduct back calculation of the model foundation soil strength. It is obtained that the soil strength reaches about 6kPa through calculation of the bearing capacity, i.e., requirements for foundation bearing capacity in the model test can be satisfied.

There are mainly three methods to fabricate the foundation soil, which are preparation of super soft soil based on thixotropy, preparation of super soft soil based on solidification and preparation of super soft soil based on low vacuum pre-pressing respectively. However, there are certain problems in three methods respectively. For preparation of super soft soil based on thixotropy, preparation of remolded soil with water content of 35% is directly made, and the viscosity is large, which requires that the foundation soil maker shall have the special internal structure and unique excavating facilities. Through comparison, simulation effects of preparation of super soft soil based on thixotropy are the best. Therefore, the method is selected for preparation of the foundation soil. The soil for test is taken from the filled earth in the artificial reclamation area in Lingang Industrial Area of Tianjin Binhai New Area.

For basic physical properties of remolded soil with water content of 35%, see Table 1.

| Soil sample | water content $\omega$ | density $\rho$ | Dry density $\rho_d$ | proportion $G_s$ | saturation $S_r$ | Void ratio $e$ | Liquid limit $w_L$ | Plastic limit $w_p$ | Cross plate strength $\tau_f$ |
|-------------|-----------------------|---------------|---------------------|----------------|----------------|-------------|-----------------|-----------------|---------------------|
| remolded    | 35.6                  | 1.88          | 1.39                | 2.72           | 100.0          | 0.955       | 33.7            | 18.0            | 6.0                 |

3.2 Fabrication of soft clay in the large flume

During simulation of interaction among wave - structure - soft clay foundation in the large scale wave flume, the flume scale is large, and the foundation earth volume for the model is large. Selection, preparation, consolidation mode and consolidation time of the model soil and measurement of soil parameters during test shall be subject to detailed research. It provides technical basis for wave - structure - soft clay foundation in the large flume.

Combination of the three-phase asynchronous motor and cycloidal reducer is adopted for the driving system of the remolded soil maker, and the rotating speed is 50r/min. Plus the self-made internal structure, the mud can be uniformly mixed without being pasted inside the mud machine. A barrel type fan is placed below the motor, so as to help motor radiation and realize continuous operation. The mud barrel can be tilted as a whole, so as to pour the uniformly prepared soil into the model groove. The laser line instrument and the meter ruler are combined for soil elevation positioning. The pore water pressure sensor is embedded when a certain height is reached. The cross plate test and static load test are conducted every 1m, so as to confirm that soil strength satisfies requirements. Finally, conduct manual screening, cover the geotextile and PVC, moisturizing and curing, and the strength can satisfy requirements after the soil is set still for 15 days.

The soil is set still for 15 days. For cross plate test results, see Figure 2. It can be seen that soil strength slowly and uniformly grows, rapid growth in the first 7 days, and slow growth 7 days later. The soil strength at both sides of the model groove is slightly larger than that in the middle. However,
the strength reaches about 6.2kPa after the soil is set still for 15 days, which can satisfy test requirements.

![Graph](image1)

**Figure 2.** Soil strength growth curve

**Figure 3.** Soil strength variation with depth

The foundation soil at the position for placing model is subject to cross plate test. For test results, see Figure 3. There is basically linear growth in soil strength with depth increase, which indicates that overall uniformity of the foundation soil is better, and the strength also satisfies test requirements.

3.3 Layout of sensors in the foundation

In order to research response in the foundation below the structure under wave action, it is the most direct means to measure the pore water pressure \(^{11}-^{13}\). Most pore water pressure sensors are arranged in the foundation soil. Five vertical rows of sensors are arranged within the range of 2m deep and 5m wide below the breakwater bedding. The vertical distance of the sensor is 0.2m, and the horizontal spacing is 0.9m. For layout of the pore water pressure sensor. The sensor is calibrated before leaving the factory, and calibration is not required during test. The sensor diameter is 8mm.

4. Main results of pore water pressure under wave action

To simulate test in case of any failure in semi-circular body at Changjiang Estuary, the existing research findings hindcast the wave with failure, and the wave conditions at failure are obtained: High water level +3.94m, \(H_1%=4.72\) m, \(H_2=3.4\) m; low water level +0.58m, \(H_1%=3.87\) m, \(H_2=2.83\) m; The crest elevation of the caisson is +2.95m, and the mud surface elevation is -7.00m.

The soil with three different water contents is tested under long-term wave action. For the soil with initial water content of about 30%, the cumulative pore water pressure is less under long-term wave action; the soil water content is changed to about 44%, and the semi-circular body is sunk by 1.2m under action of small wave height of 1m; the soil water content is changed to about 35% again, there is accumulation of pore water pressure to a large degree under long-term wave action, and there is sedimentation in caisson. Photo after placing the model of semi-circular body is shown in Figure 4. Photo of test process is shown in Figure 5.

![Photo](image2)

**Figure 4.** Photo after placing the model

![Photo](image3)

**Figure 5.** Photo of test process

4.1 Test results of water content 30%

Test conditions for action of long-term wave cycle of the semi-circular body model test at Changjiang Estuary: the action of long-term wave cyclic load from small wave height to large wave height is conducted at the high water level: (1) significant wave height 1m, period 7.8s, number of waves 1,500; (2) significant wave height 1m, period 7.8s, number of waves 1,500; (3) significant wave height 2m, period 7.8s, number of waves 1,500; (4) significant wave height 3m, period 7.8s, number of waves 1,500. The test wave heights are 1m, 2m and 3m respectively. The maximum cumulative pore pressure
is 2.27kpa in the first row at depth 1m after wave action. See Figure 6 for changes in pore water pressure.

4.2 Test results of water content 44%
Wave conditions for semi-circular model test at Changjiang Estuary: Half load and high water level (1)wave height of 0.5m, period 7.8s and wave number 1000; (2) wave height 1m, period 7.8s and wave number 1000. Under action of 0.5m wave height, the cumulative change value of the pore pressure and soil pressure is small, not exceeding 0.4Kpa at maximum. The semi-circular caisson is sunk by 1.2m under action with wave height of 1m. It can be seen from the results that the maximum cumulative pore pressure is 3.10kpa in the 4th row at depth 0.2m. Due to high water content, soil at some places has failure in the 4th row at depth 1.0m. See Figure 7 for changes in pore water pressure.

4.3 Test results of test results of water content 35%
Wave conditions for semi-circular model test at Changjiang Estuary: Full load and high water level. The caisson is subject to three continuous tests with wave height 1.5m, period 7.8s and wave number 1000. Finally, the caisson has substantial settlement finally. For final cumulative change value of the pore pressure sensor. The maximum cumulative pore pressure is 12.33kpa in the 1st row at depth 0.2m. Under long-term wave action, the wave force generates large action on the structure transiently. The structure transfers force to the foundation, and the excess pore water pressure is generated in the foundation. The pore water pressure declines in case of foundation failure. In case of foundation failure, the structure has tiny displacement or sinking. After stability is reached, the wave force continues action, and the above process is repeated for the foundation; after the pore pressure is accumulated to a certain value, the structure generates large displacement or sinking, the foundation has failure, and the structure is unsuitable for continuous work. There is unequal settlement of the caisson after test, and the maximum settlement is 0.43m. See Figure 8 for changes in pore water pressure. See Figure 9 for soil failure photograph.
4.4 Changes in pore water pressure under short-time action with different wave heights

With increase in wave height, the amplitude of pore pressure is continuously increased. The amplitude of pore pressure in the first row in front of the dike is the maximum at depth 0.6m. With increase in action wave height, the pore water pressure is progressively increased. The pore water pressures under action with wave heights of 0.6m, 0.5m, 0.4m, 0.3m and 0.2m, the pore water pressures are 1.64Kpa, 1.51Kpa, 1.05Kpa, 1.00Kpa and 0.59Kpa respectively.

Table 2 Comparison of the amplitude of pore pressure under the action of different wave heights in the first row of pore pressure

| Sensor depth | 0.6m | 0.5m | 0.4m | 0.3m | 0.2m |
|--------------|------|------|------|------|------|
| 0.2m         | 0.77 | 0.77 | 0.34 | 0.38 | 0.16 |
| 0.4m         | 1.34 | 1.32 | 0.80 | 0.76 | 0.43 |
| 0.6m         | 1.64 | 1.51 | 1.05 | 1.00 | 0.59 |
| 0.7m         | 0.65 | 0.65 | 0.36 | 0.33 | 0.19 |
| 0.8m         | 0.70 | 0.69 | 0.36 | 0.35 | 0.21 |
| 1.0m         | 0.75 | 0.72 | 0.35 | 0.37 | 0.22 |

5. Conclusion and prospect

(1) The large scale flume wave test indicates that the soil strength grows with increase in the setting time, fast growth at the early stage and slow growth at the later stage; Under action of long-term wave cyclic load, the change laws of different cumulative pore water pressure are obtained by changing the soil water content, and the cumulative pore pressure is small when the water content is low. It can be seen from the test results that the change law of the pore water pressure can be obtained by changing the soil water content, which provides technical support to research softening law of the soft clay.

(2) The pore water pressure is changed with wave action. Influence of pore pressure is increased with increase of wave height, the influence of pore pressure is the maximum at a certain depth.

(3) The test of wave - structure - soft clay foundation is conducted in the large scale wave flume. The time for remodeling soft clay is long, the cost to make the soft clay is high, and the time for model placement and debugging of the testing instrument is long. Therefore, construction scheme shall be prepared in advance during modeling process of the large scale flume, and the reasonable test method and construction steps shall be determined. The test group and test sequence shall be reasonably selected during test.

(4) Consumption of the remodeled soft clay is small in the large scale flume, and it is very difficult to guarantee soil uniformity, which shall be guaranteed as much as possible during similar test afterwards.

(5) The pore water pressure sensor is buried during preparation of the soft clay. With preparation of the subsequent topsoil, the sensor position will be changed, and more reasonable sensor embedding mode will be found in future tests.

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