Research on settlement analysis of large caisson foundation by centrifuge model test

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Abstract: With the increasing scale of caisson foundation in the construction of long-span bridge engineering in China, the overall settlement of large caisson foundation is vital to the construction and safe operation of long-span bridge. Taking the large caisson foundation of Changtai Yangtze River Bridge as the engineering ground, the overall settlement of this caisson foundation was analyzed in detail at the construction stage of Changtai Yangtze River Bridge by centrifuge model test based on the distribution of actual stratum. The test results demonstrated that the overall settlement was about 225mm when the construction of Changtai Yangtze River Bridge is finished, the settlement curve can be divided into three stages with the construction process of Changtai Yangtze River Bridge, and they are slow growth, rapid deformation and deformation stability. The study provides important reference to the design of large caisson foundation of Changtai Yangtze River Bridge, and it also has significant referential meaning to the construction of similar caisson foundation.

1. Introduction

With the rapid development of long-span bridge construction in China, more and more caisson foundations are popularly used as the main pier or anchorage foundation of long-span Bridge[1]. Due to the importance of overall settlement of caisson foundation to the construction and safe operation of bridge, it is worthy of further study to the bridge construction for reasonable evaluation of the settlement deformation caused by construction loads.

For the principle of the centrifuge model test, it makes up for the stress loss caused by model scaling through increasing centrifugal acceleration, which can truly reflect the mechanical behavior in actual engineering[2-4]. Right now, the centrifuge model test has been widely used in geotechnical engineering because it can effectively analyze practical problems of geotechnical engineering and its results can provide important reference to practical engineering. Up to now, the caisson foundation had ever been studied by the centrifuge model test, for example, the subsidence process of caisson foundation of Hutong Yangtze River Bridge was simulated in order to study the lateral frictional resistance, and furthermore, the distribution law of sinking resistance was also comprehensively studied by different depth conditions through the centrifuge model test. From the previous study[5-9], it can be seen that the
results of the centrifuge model test is reliable, which can effectively simulate the mechanical behavior of soil in actual engineering.

Taking the large caisson foundation of Changtai Yangtze River Bridge as the engineering ground, this paper emphasize the overall settlement of large caisson foundation by the centrifuge model test, and the settlement curve was obtained with the construction process of this bridge. The overall deformation of the large caisson foundation was rationally predicted and the research results have reference meaning to similar caisson foundation construction.

2. Project overview of Changtai Yangtze River Bridge
Changtai Yangze River Bridge connects Changzhou city and Taizhou city. It is a railway and road cable-stayed bridge with two towers and two cable planes arranged asymmetrically. The span of main navigation channel bridge is 1176m, which is the longest cable-stayed bridge in the world. The overall arrangement is shown in figure.1.

![Main Bridge of Changtai Yangtze River Bridge](image)

The main tower foundation is located in deep sedimentary soil, and the caisson foundation are planned to used in order to meet the strict requirement of upper bridge structure and liner control. The round-ended form is adopted for the caisson foundation of this bridge. At the bottom of the caisson foundation, it is 95m long, 57.8m wide and the radius of the round end is 28.9m, at the top surface of the caisson bridge, it is 77m long, 39.8m wide and the radius of the round end is 19.9m. The total height of the caisson foundation is 72m, and it is made of steel shell concrete from the top to the bottom, which is the largest steel caisson in water in this world.

It is quaternary strata in the caisson foundation area with deep overburden, which are mainly alluvial and lacustrine clay and sandy soil. The burial depth of the caisson foundation is about -65m under the water. According to quaternary strata, there is a continuous layer of silty clay between -72m and -84m, which is with certain structure, the water content and porosity ratio are both high, and it varies greatly for the physical and mechanical properties. Besides, there is also a 5m thick silty clay between -87.5m and -91m. Due to great influence on the overall settlement of the caisson foundation, the silty clay below the caisson foundation needs to be further studied.

3. Centrifuge model test
Fig.2 is the TK-C500 geotechnical centrifuge equipment. For this centrifuge equipment, the maximum acceleration is 250g, here, g is gravity acceleration, the maximum effective load is 5 ton, the maximum radius of rotation is 5m, and the maximum size of the model box is 1.2m×1.0m×1.2m (length×width×height). For the caisson foundation adopted in the bridge, the total self-load is about 0.5 million tons and the construction period is about 21 months. For the upper bridge structure, the total load is about 0.28 million tons, and the construction period is about 38 months.

3.1. Test model
The external size is 95m×57.8m×72m (length×width×height) of the actual caisson foundation in this bridge, and the size of the model box is 1.2m×1.0m×1.2m (length×width×height). Considering the
influence of the boundary effect, the half of the symmetrical caisson foundation was selected for the centrifuge test, and the similarity ratio was comprehensively selected as 150, that is, the acceleration of the centrifuge is 150g when the equipment is stably operating during the test procedure. Figure 3 is the sketch of the design for the caisson foundation model. Based on the similarity ratio and actual size of the caisson foundation, the model size is 317mm×385mm ×480mm (length×width×height), and the model of the caisson foundation was made with 6061 alloy aluminum material. Figure 4 is the solid model of the caisson foundation after finishing the production.

For the soil below the caisson foundation, the physical and mechanical parameters of each layer were determined by indoor geotechnical tests after field drilling sampling, which is shown in Table 1. Before making the model soil, the drainage equipment was put into the bottom of the model box for saturation after completing the model. In order to reduce the influence of the boundary effect on the test, Vaseline was used to the inner wall of the model box to simulate the semi-infinite field.

| type          | density ρ(g/cm3) | Natural water content (%) | Friction angle (°) | cohesion(KPa) |
|---------------|-----------------|---------------------------|--------------------|---------------|
| silty clay    | 1.89            | 33.6                      | 11.1               | 43.6          |
| Medium sand   | 1.98            | 25.6                      | 36.8               |               |
| silty clay    | 1.91            | 30.2                      | 14.9               | 34.8          |
| Coarse sand   | 1.97            | 12.8                      | 42.1               |               |

The foundation soil of the model box is made with sand rain method for sand and vibration compaction method for silty clay. After all the soil is filled based on the actual stratigraphic distribution, water is slowly injected in two times from the bottom of the soil to make the soil fully saturated. Figure 5 is the solid model diagram after completion. According to the requirement of calculating depth of
foundation settlement in relative specification in China, it was comprehensively determined that the soil in the range of 62m below the bottom of the caisson foundation is considered in this test, and it includes almost silty clay layer below the bottom of the caisson foundation.

3.2. Arrangement of monitoring points
In order to obtain the settlement curve of the caisson foundation with the constructing process of this bridge, four HG-C1200 laser sensors with a range of 200±80mm were arranged to monitor the settlement on the upper surface of the caisson foundation in the model box, and the locations of the laser displacement sensor are shown in Fig.6.

![Figure 6 Locations of monitoring points](image1)

![Figure 7 earth pressure monitoring points (unit: cm)](image2)

Based on the actual stratigraphic distribution, there is a silty clay layer with about 7m thickness distributed below the bottom of the caisson foundation, which is also a concern in this test, therefore, the mini earth pressure sensors were placed on the surface and the middle area of the silty clay soil in this test, and the locations of the monitoring points on the surface of the soil are shown in figure.7, as well as in the middle area of the soil.

3.3. Test process
The loading system of the centrifuge model test mainly includes the frame of the upper part of the model box, the loading beam, the loading equipment placed on the beam and the controller, which is shown in fig.8. Furthermore, the hierarchical loading stage can be set in the loading system based on the requirement, and the automatic loading is realized under high centrifugal environment. According to the key stage during the bridge construction, the loading parameters were obtained on the basis of the similarity ratio and the segment-loading was carried out in this test. After the one-stage load is applied, the settlement and earth pressure are observed till they are stable, then, the next level of load will be applied until all the loads are completely applied in the test.

![Figure 8 the loading equipment](image3)

There are totally four steps in this test, which is demonstrated as in the following.
(1) After model making is completed, the model box is hoisted into the centrifugal basket and properly placed, and then, the loading beam, loading equipment and other related accessories are installed, before starting the centrifuge test, arrangement of the wiring and sensors should be completed.

(2) Taking 20g as the interval, the load is gradually applied until 150g and the centrifugal testing machine needs to be operating for 10 min in order to restore the initial stress state of the soil. The loading test can be carried out when the monitoring values about the displacement and earth pressure are stable.

(3) Based on previous work above, the loading system software is opened, the loading data is imported, and then the loading test can be operated. During the operation, photos and videos can be taken at any moment of this test.

(4) When the load is completely applied, the corresponding test data is saved and the model box can be hoisted out of the centrifugal basket after finishing the test.

4. Results analysis
The settlement curve of caisson foundation is obtained by real-time monitoring in this test for simulating the construction process of this bridge. Due to small deviation of settlement observed at four monitoring points, the average settlement is used to represent the overall settlement of the caisson foundation, shown in figure.9.

### Table 2
| Index | Key stage      | Time (month) | Load (KN) |
|-------|----------------|--------------|-----------|
| 1     | Lower tower    | 7            | 691385    |
| 2     | Middle tower   | 8            | 1696699   |
| 3     | Upper tower    | 10           | 1870007   |
| 4     | Kingpost       | 8            | 2452937   |
| 5     | Accessory structure | 3   | 2801186   |

![Figure 9](image_url) Settlement of caisson foundation by test

![Figure 10](image_url) Earth pressure monitoring results

From the table.2, there are five key stages of structure construction, and the figure.10 is the corresponding settlement curve. The first stage is the construction of the lower tower, the construction load is about 69000 tons, and the foundation settlement is 6.38 mm, which belongs to the slow growth stage. The second stage is the construction of the central tower, the load is about 0.17 million tons, and the corresponding settlement is 58.26mm. For the third stage, it is the construction of upper tower, the load reaches about 0.19 million tons and the corresponding settlement is about 110.75mm, in this stage, the settlement of the caisson foundation increases sharply. The fourth stage is the main girder construction, the load is about 0.25 million tons, the sinking speed is slower than that of upper tower construction, and the corresponding settlement is 209.46mm. The last stage is accessory structure construction, the load reaches the maximum 0.28 million tons, the settlement of the caisson foundation...
tends to be gentle, and the corresponding settlement is 226.25 mm. It can be concluded that the overall settlement of caisson foundation increased with the load increase of structure construction, and the deformation can be roughly divided into three stages, slow increasing, rapid deformation, and settlement convergence. It belongs to slow increasing stage from the upper structure construction to middle tower construction, sharp deformation stage from middle tower construction to main girder construction, and settlement convergence stage from main girder construction to accessory structure construction.

The earth pressure of the soil observed in the model test is shown in Fig. 10. The model test value means monitoring value in the centrifuge model test, and the calculated value is the earth pressure value at the middle position of the silt clay calculated based on actual soil density and depth. The comprehensive bulk density of soil is set as 20 kN/m3, here, it needs to state that the influence of stress diffusion from the bottom of caisson foundation to the silt clay is not considered in the calculation value.

From the figure 10, it can be seen that the calculation value is slightly larger than the monitoring values, the calculation values linearly increases with the increase of engineering load, which is consistent with the change of the monitoring values. The earth pressure by calculation is large than the monitoring value, which would be caused by the stress diffusion from the bottom of the caisson foundation to the middle position of silt clay layer. For the calculation value, it doesn’t consider the stress diffusion above mentioned, however, the model test reflects the influence of stress diffusion, therefore, the calculating value is a little large than the monitoring value.

5. Conclusion
(1) The centrifuge model test was used to study the deformation of large caisson foundation during the construction stage of Changtai Yangtze river, the test results demonstrated that the overall settlement is about 225 mm when the construction of upper bridge structure is finished, which meets the requirement of the deformation control of the caisson foundation during bridge construction stage.

(2) The settlement curve of caisson foundation along with the construction of the bridge can be roughly divided into three stages, slow increasing, rapid deformation, and settlement convergence. It belongs to slow increasing stage from the upper structure construction to middle tower construction, sharp deformation stage from middle tower construction to main girder construction, and settlement convergence stage from main girder construction to accessory structure construction.

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