Research Article

Mechanical Performance of Deep Circular Caisson Sinking in Deep Layered Soft Soil

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In order to study the mechanical behavior of open caisson foundation in the Wenzhou area, combined with the characteristics of the soil layer in the Wenzhou area, based on the field measurement and investigation of a wide range of engineering cases, this project studies the mechanical properties of open caisson sinking in soft soil stratum and optimizes the construction parameters through the combination of field measurement, numerical simulation, and theoretical calculation, while ensuring the smooth sinking of the open caisson, control the deformation effect of the soil around the open caisson to serve the urban construction. The research results can directly serve the whole process of design, construction, measurement, and control of open caisson engineering. It has engineering practical significance and can be used as a reference for similar projects.

1. Introduction

With the development of urban infrastructure construction, the shortage of soil resources has gradually become prominent. Urban infrastructure construction is also gradually developing underground to alleviate the land dilemma of urban construction. Underground engineering construction has become an important content of current engineering construction. As a foundation pit construction technology for underground space construction, open caisson technology adopts the construction method of on-site structural pouring and soil borrowing and sinking. Open caisson technology has been developed for more than 170 years and plays an important role in urban construction [1–4] With small section size, large stiffness, high bearing capacity, good impermeability, good durability, and high utilization rate of internal space, open caisson structure can be constructed under various complex terrain, geology, and narrow site and has little impact on adjacent buildings and structures, which makes open caisson irreplaceable in underground structures and construction methods and widely used in urban construction, such as large underground gas storage tanks, oil storage tanks, reservoirs, and large underground parking lots.

There are many classification methods for open caisson, including circular open caisson and rectangular open caisson [5, 6] according to the plane shape. In the field of tunnel and highway engineering, the cross-section of caisson is usually circular. Rectangle is usually used in port engineering or bridge engineering. At present, theoretical calculation, field measurement, numerical simulation, and indoor model test are mainly used to study the foundation bearing capacity, internal force of caisson structure, and settlement deformation of surrounding soil layer at home and abroad.
In the theoretical analysis and research, Soubra [7] studied the static bearing capacity of shallow strip foundation under the upper bound method framework of limit analysis theory and considered M1 and M2 motion allowable failure mechanisms at the same time. Zhao [8] made a theoretical study on the ultimate bearing capacity of the blade foot of the pneumatic caisson and drew corresponding conclusions. Liu et al. [9] drew lessons from the linear elastic foundation reaction method of piles to find a modified solution suitable for the horizontal displacement of the open caisson. Guangbao et al. [10] theoretically analyzed the control construction technology of large open caisson in combination with quaternion theory, adopted a new algorithm based on a noniterative strict mathematical method to calculate the spatial geometric state parameters of caisson, derived the spatial rotation matrix from quaternion, and calculated the positive definite matrix and unit quaternion by minimizing the objective function.

In the field measurement research, Guo [11] measured the whole process of construction subsidence of the first pneumatic caisson in China. Allenby et al. [12] studied in detail four open caisson operations in the wastewater treatment plant under the framework agreement for Scottish water solutions which went on very successfully recently. The use of open caisson technology allows the shaft structure to sink gradually from the surface to the predetermined depth under the control of self-weight or with the help of caisson Jack. Chavda et al. [13] designed and conducted a sinking simulation test according to the sinking structure of the largest caisson in the world. Also, the migration track of sand outside the caisson and the settlement of the riverbed after sinking are measured and analyzed. Peng et al. [14] developed an automatic construction system for caissons. The system can carry out unmanned excavation and remote operation of excavators based on remote control technology, vertical screw conveyors for continuous soil discharge, and integrated real-time monitoring system, in which all excavation and soil removal are completed remotely by workers on the ground.

In the numerical simulation research, Xu [15] used the finite element software PLAXIS 3D to establish the three-dimensional numerical simulation of the data based on a centrifuge experiment. With the increase of load, the sinking of open caisson increases nonlinearly. Gui et al. [16] used the finite element software ABAQUS to analyze the active Earth pressure of the rigid retaining wall. The fill behind the wall was sand, and the Mohr-Coulomb constitutive model was used to simulate the stress-strain behavior of the soil. Compared with the Rankine analysis results, the simulation results were larger, and the error was about 10%. Lai et al. [17] proposed the CEL coupling Lagrange method combined with excavation penetration to study the influence of caisson sinking in an undrained clay layer on the surrounding settlement.

In the model test research, Jing and Hu [18] took the actual engineering open caisson as the reference and set the model similarity ratio as 1:100 for an indoor test. The research results show that the greater the buried depth and the lower the water content, the greater the impact on the foundation bearing capacity. Wang et al. [19] took the engineering open caisson model as an example, made an indoor model test model, analyzed the influence relationship between the sinking depth and the side friction, and explained the reason why the side friction first increased and then decreased in combination with the theoretical analysis results. Jiang et al. [20] designed and conducted a settlement simulation test based on the settlement construction of the largest open caisson in the world.

To sum up, although scholars at home and abroad have done a lot of research on open caisson and caisson, there is less research on the measured stress and the change law of structural internal force during the sinking of deep circular open caisson in the deep soft soil layer. At the same time, due to different geological conditions, open caisson types, and construction methods, the direct application has certain limitations, and there is a large gap between the structural design of open caisson and engineering practice. Therefore, it is necessary to carry out on-site monitoring of large-scale circular open caisson in deep soft soil layer. At the same time, it provides theoretical and numerical reference basis for large-scale open caisson foundation design and reference experience for on-site construction.

2. Overview of Supporting Projects

2.1. The Profile of Project. This paper relies on the project for a river crossing power tunnel project in Wenzhou, serving the laying of high-voltage cables on both sides of Oujiang River. The inner diameter of the working open caisson of the project is Φ12 m, the wall thickness is 1.1 m, and the total height is 32.42 m. The width of the cross beam of the inner wall is 1.9 m, and the height is 1.5 m. The width of the blade foot surface is 0.6 m, and the height of the blade foot slope is 0.8 m. The open caisson is raised for 6 times and sunk for 2 times. The first, second, and third sections are the first subsidence, and the third, fourth, and fifth sections are the second subsidence. The standard value of self-weight of the first sinking open caisson is 2274.57 t, and the dry sinking method is adopted. The standard value of self-weight of the second sinking open caisson is 3902.13 t, and the wet sedimentation method is adopted. The foundation structure of the open caisson is shown in Figure 1.

2.2. Engineering Geological Conditions. The stratum conditions of the construction site mainly distribute fine sand, silt plus silt, silt, and other strata from the surface down. The surface water at the construction site is mainly Oujiang River water, and the groundwater is underground phreatic water and confined water. Underground phreatic water mainly occurs in (1) silt mixed silt layer and (2) silt containing silt layer, and underground confined water mainly occurs in (1) silt containing silt layer, (2) cohesive silt layer, and (3) pebble layer. During the survey, the depth of groundwater level revealed by borehole CK1 is 3.7 m. The composition and characteristics of foundation soil are shown in Table 1 from top to bottom.

In the field investigation, the undisturbed soil samples were taken with a thin-wall sampler, the electric measurement method was used for the field vane test, and the
The specification of the plate head was 100 mm × 50 mm. A large number of direct shear tests, triaxial unconsolidated undrained test (UU), consolidated undrained test (CU), unconfined compressive strength test, and indoor micro vane test were carried out in the laboratory test. According to the test results, after statistical analysis, the main physical and mechanical indexes of soil layer are shown in Table 2.

2.3. The Construction Method for Open Caisson. Due to the relatively large length, high gravity center, and poor stability of the open caisson, and considering the impact of the construction of the open caisson on the surrounding buildings and adverse geology (the open caisson sinks through the water-bearing sand layer, the water level is affected by the water of Oujiang River, and it is easy to cause flowing soil and sand under the action of dynamic water), the scheme of section and step sinking is adopted. At the same time, due to the high groundwater level and the influence of Oujiang River water, it is easy to cause flowing soil and sand under the action of dynamic water. In order to reduce the infiltration of groundwater into the foundation of the open caisson during the sinking process of the open caisson, the Larsen pile is arranged 3 M away from the outer wall of the open caisson as a water stop curtain. The Larsen pile is 18 m long and 0.6 m wide. The fabrication of open caisson sinking in sections and times is shown in Table 3.

3.1. Field Measurement Scheme

3.1.1. Sensor and Installation Location Information. The field measurement experiment is mainly divided into two parts, one is the end of the blade foot (tread and inclined plane), and the other is the caisson wall. The arrangement of blade foot soil pressure sensor, side wall soil pressure sensor, and reinforcement stress sensor is shown in Figures 2 and 3.

First, the soil pressure sensor is buried at the edge foot of the open caisson. 4 sensors are buried at the bottom of the edge foot and the slope of the edge foot. Among them, 3 soil pressure sensors are buried on the slope of the edge foot with a length of 1 m, and one soil pressure sensor is buried at the center of the bottom of the edge foot. Sensors are buried along four sections of the annular open caisson, 12 soil pressure sensors are buried on the inclined plane, and 4 soil pressure sensors are buried on the edge pedal surface. The height of the soil pressure sensor at the inclined plane of four sections of the annular open caisson is exactly the same, and the elevation of the soil pressure sensor at the inclined plane is −32.22 m, −32.02 m, and −31.82 m, respectively. Among them, the JMZX-5080a steel string double membrane soil pressure sensor with a measuring range of 8.0 MPa is used for the foot surface and foot slope of the open caisson.

Second, soil pressure sensors are buried around the circular open caisson, 4 soil pressure sensors are buried in each section, and a total of 32 soil pressure sensors are buried in 8 sections of the side wall. The section elevations of the side wall soil pressure sensor are −32 m, −31.5 m, −26.9 m, −22.2 m, −17.5 m, −12.8 m, −8.1 m, and −3.4 m, respectively. Among them, the sidewall soil pressure sensor adopts JMZX-5020a steel string double membrane soil pressure sensor produced by Changsha Jinma measurement and Control Technology Co., Ltd., with a measuring range of 2.0 MPa.

Table 2: The main physical and mechanical indexes of soil layer.

<table>
<thead>
<tr>
<th>The name of soil layer</th>
<th>Bulk unit weight of soil (kN/m³)</th>
<th>Internal friction angle (°)</th>
<th>Cohesion (kPa)</th>
<th>Compression modulus (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>17.5</td>
<td>13.7</td>
<td>23.5</td>
<td>3.15</td>
</tr>
<tr>
<td>Sludge mixed with silt</td>
<td>17.2</td>
<td>20.7</td>
<td>5.5</td>
<td>2.39</td>
</tr>
<tr>
<td>Silt with sludge</td>
<td>18.9</td>
<td>16.0</td>
<td>11.7</td>
<td>6.81</td>
</tr>
<tr>
<td>Sludge</td>
<td>17.1</td>
<td>13.8</td>
<td>13.0</td>
<td>3.26</td>
</tr>
<tr>
<td>Silt with sludge</td>
<td>18.9</td>
<td>17.4</td>
<td>15.3</td>
<td>6.70</td>
</tr>
<tr>
<td>Mucky clay</td>
<td>17.5</td>
<td>19.4</td>
<td>14.8</td>
<td>3.41</td>
</tr>
<tr>
<td>Clay silt</td>
<td>20.2</td>
<td>25.8</td>
<td>15.3</td>
<td>9.38</td>
</tr>
</tbody>
</table>

Table 3: Subdivision and subdivision of open caisson (unit: m).

<table>
<thead>
<tr>
<th>Production layering</th>
<th>Fabrication height</th>
<th>Total height of layers</th>
<th>Sinking process</th>
<th>Sinking height</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>5.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Second</td>
<td>6.20</td>
<td>16.2</td>
<td>Drainage subsidence</td>
<td>15</td>
<td>Sinking elevation + 0.9 to −14.1</td>
</tr>
<tr>
<td>Third</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fourth</td>
<td>3.87</td>
<td>16.22</td>
<td>Undrained subsidence</td>
<td>17.2</td>
<td>Final settlement elevation −31.52</td>
</tr>
<tr>
<td>Fifth</td>
<td>6.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sixth</td>
<td>5.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.1.2. Data Acquisition. The setting of the measured frequency is based on the whole process of the measured sinking of the open caisson and is adjusted according to the changes in the on-site construction conditions. The sensor data are transmitted continuously. The value of the acquisition instrument needs to be calibrated when it arrives at the...
site, and the initial value needs to be collected after the installation of the sensor. The frequency of data acquisition is also different according to the different sinking depths of the site. During the first sinking of the open caisson, the detection system collects phase data every five minutes, 288 phase data can be collected every day, the measured frequency of the second sinking is adjusted to collect once every ten minutes, and 144 phase data can be collected every day. When the caisson is sinking to the design elevation, it is adjusted to collect every thirty minutes, and 48 phases of data can be collected every day. If there is any special case, the detection frequency can be adjusted at any time, as shown in Table 4.

In this field measurement, the soil pressure, reinforcement stress sensor, and other data are collected by the automatic measurement system. The field data acquisition system adopts JMZX-32a intelligent string integrated acquisition system. A single set provides 32 channels. A total of 3 sets to 96 channels are connected in series in this test. The measured data are transmitted to the cloud platform through the wireless transmission system. The measured cloud platform completes the operations of data acquisition frequency, acquisition time, data export, and so on. The actual measurement of the project began on September 6, 2018, and ended on March 15, 2019. Continuous monitoring was carried out on the heightening and sinking of the open caisson.

3.2. Analysis of Measured Law

3.2.1. Measured Law of Soil Pressure

(1) Analysis of the Measured Law of Soil Pressure at the Bottom of Blade Foot. The variation curve of soil pressure at the bottom of the blade with depth is shown in Figure 4.

It can be seen from Figure 4 that the soil pressure of the first sinking of the open caisson is between 0 and 0.5 MPa, the curve is basically vertical, and the soil pressure is basically unchanged. From the end of the first sinking to the design elevation, when the sinking depth of the open caisson is 13 m~25 m, the soil pressure at the bottom of the blade increases approximately linearly with the increase of the sinking depth, and the maximum soil pressure is 5.32 MPa. From the depth of 25 m to the end of sinking, the soil pressure at the bottom of the edge foot of the open caisson tends to be stable and decreases with the increase of the penetration depth. After analyzing the construction conditions, it can be found that the cushion at the bottom of the blade foot has not been completely removed before the first sinking of the open caisson. Before the second heightening, with the increase of the soil depth and the excavation of the "big pot bottom" working condition, the soil pressure at the bottom of the blade and foot increases with the soil depth during the second sinking. When the open caisson sinks to the silt layer, there is a great difference in the soil pressure at the bottom of the blade foot. The sinking state of the open caisson can be judged from the field elevation difference measurement and soil pressure measurement, and it can also be reflected from the side. The installation of soil pressure sensor at the bottom of open caisson can be used to give early warning of possible partial or sudden settlement during open caisson construction.

(2) Analysis of the Measured Law of Soil Pressure on the Slope of Blade Foot. The instrument of the soil pressure sensor on the first layer of the blade foot inclined plane is damaged in the sinking stage. Among them, one instrument on the second and third layers of the inclined plane is damaged, respectively. The soil pressure variation curve of the measuring points of these two layers is shown in Figure 5.

It can be seen from Figure 5 that the slope soil pressure value remains stable before the first open caisson sinking. The soil pressure value of the second layer of the inclined plane begins to decrease rapidly with the increase of the soil penetration depth. After the depth exceeds 15 m, its value increases rapidly, and the maximum value appears at 25 m of the soil penetration depth. The soil pressure value of the third layer of the inclined plane starts to increase slowly after the soil penetration depth exceeds 13.5 m, reaches the maximum value when the soil penetration depth is 24 m, and remains unchanged until the sinking of the open caisson. Through specific analysis, it can be seen that during the sinking process of the open caisson, the change trend of the measured data of the measuring points on the same side tends to be consistent on the whole and shows the same increase and decrease. Before the end of the first sinking, the bottom of the open caisson blade foot has not been completely removed, the open caisson slope is in a void state, and the blade foot slope is not stressed. With the increase of depth, the soil on the side wall of the open caisson tends to move more and more into the open.
(3) Analysis of the Measured Law of Tread and Slope Stress. Take the soil pressure of the same side tread and the inclined plane for comparison. The stress and displacement comparison of the open caisson tread and the inclined plane are shown in Figure 6.
It can be seen from Figure 6 that when the soil penetration depth is 0∼19 m, the soil pressure of the blade foot surface is close to that of the inclined plane at the similar position, and the load is borne by the blade foot, and the inclined plane is small. During this period, the displacement of each measuring point of the open caisson fluctuates greatly, and the open caisson is in the rapid sinking stage. When the soil depth is 19∼32 m, the resistance gap between the tread and the inclined plane gradually becomes larger, and the blade pedal surface bears a large part of the sinking resistance, which is related to the excavation method of sinking the open caisson and the height of the mud surface inside the blade foot.

In the sinking process of the open caisson, the soil pressure on the blade foot surface increases with the increase of depth, and the soil pressure on the slope of the blade foot changes little because the upward resistance is mainly provided by the side friction, the blade foot surface, and the slope. With the increase of the sinking depth of the open caisson, the side friction increases linearly and slowly, while the bottom of the open caisson is constantly excavated, and the soil pressure on the slope of the blade foot basically remains unchanged or increases slowly. The upward resistance of the open caisson mainly comes from the reaction of the blade foot surface.

The main reason for the fluctuation of the soil pressure value of the blade foot surface and slope is that when the upward resistance is less than the downward gravity, the open caisson begins to sink, the soil pressure value of the blade foot surface decreases, and the soil layer height of the blade foot slope increases gradually. The closer it is to the bottom of the blade foot slope, the greater the soil pressure of the slope. When the sinking resistance is greater than its own gravity, the sinking speed slows down. With the increase of sinking resistance, the open caisson is in a slow sinking or static state. At this time, the stress state of the open caisson can be changed by digging again.

(4) Analysis of the Measured Law of Soil Pressure on the Side of Open Caisson. Because the sinking of open caisson is always a dynamic process, and the stress of its sidewall soil pressure is very complex, the classical Rankine soil pressure theory is used to explain the variation law of open caisson sidewall soil pressure. The sinking and tilting state of the open caisson is shown in Figure 7. In the figure, \( H \) is the sinking depth. When the open caisson sinks to the right, point B on the left will produce passive soil pressure squeezing the surrounding soil, and point A will leave the soil to produce active soil pressure. On the contrary, active soil pressure will be generated at the bottom of the right side of the open caisson, and the right side squeezed by the upper soil will produce passive soil pressure.

The comparison between the side wall soil pressure values at different depths in the sinking of open caisson with different sections and the classical soil pressure theoretical values is shown in Figure 8.

It can be seen from Figure 8 that the side wall soil pressure of different sections is basically greater than the active soil pressure and less than the passive soil pressure. However, the distribution of soil pressure corresponding to different buried depth positions is not exactly the same, but there are obvious differences. Combined with the analysis of the height difference and speed of the sinking of the open caisson, it can be seen that the sinking speed of the open caisson is fast in the early stage, the sinking resistance is mainly borne by the side wall and the bottom of the blade foot, the soil pressure on the side wall gradually increases, the open caisson always swings and sinks left and right in the early stage, and the soil pressure fluctuates greatly. When the
Figure 7: Slope diagram of open caisson.

(a) Active soil pressure
(b) Passive soil pressure
(c) Active soil pressure
(d) Passive soil pressure

Figure 8: Continued.
open caisson sinks to about 20 m, the slender ratio of the open caisson gradually increases. By controlling the sinking speed of the open caisson, the sudden sinking and partial sinking of the open caisson can be prevented. After the depth of 25 m, the soil pressure reaches the peak value. Before the open caisson sinks to the design elevation, the soil pressure decreases continuously, and the soil pressure on the side wall is close to the active soil pressure. The variation law of the soil pressure on the side wall of the open caisson increases first and then decreases can be explained by the pressure relaxation phenomenon, which is shown in Figure 9.

It can be seen from Figure 9 that after the soil inside the open caisson is removed, the soil at the edge foot of the open caisson tends to move inward, forming a pressure relaxation phenomenon, and the position of this phenomenon moves downward with the increase of the sinking depth of the open caisson. When the sinking depth of the open caisson is small, the pressure relaxation near the blade foot is not obvious. The soil pressure on the side wall of the first sinking of the open caisson increases approximately linearly. With the increase of the sinking depth, the soil pressure on the side wall changes nonlinearly.

In order to avoid the influence of open caisson inclination on sidewall soil pressure data, the soil pressure of sidewall soil pressure sensors on different sections at the same penetration depth is selected for comparison when the height difference is small. The obtained curve of the soil

![Figure 8: Variation curves of soil pressure on sidewalls with different buried depths.](image-url)
pressure on the side wall varying with the depth of the open caisson is shown in Figure 10. It can be seen from Figure 10 that when the buried depth of the open caisson continues to increase, the measured value of the side wall soil pressure of each section tends to increase. When the soil depth is small, the soil pressure on the side wall increases greatly. When the buried depth of the soil pressure sensor is greater than 20 m, the growth rate of the side wall soil pressure begins to slow down. When the open caisson sinks to the depth of 25 m, the soil pressure value of the depth of 5.5 m from the blade foot is greater than the pressure value of the depth of 0.4 m, which verifies that the stress relaxation effect will occur at the bottom of the blade foot in the stage of soil taking and sinking.

3.2.2. Analysis of Measured Law of Shaft Wall Soil Lateral Friction. At present, there is no set of theory and method to directly measure the side friction at home and abroad. In engineering application [20], the side friction is generally calculated by measuring the strain or stress, and its principle is to obtain the side friction through the stress difference.

(1) Analysis of Measured Law of Soil Sidewall Friction. The side wall friction of soil with different buried depths is shown in Figure 11. It can be seen from Figure 11 that when the depth of the open caisson is small, the side wall friction of the open caisson increases with the increase of the depth. When the depth of the open caisson is greater than 7.1 m, the distribution form of the side friction changes from linear to nonlinear, and the overall distribution form increases first and then decreases. Literature research shows that when the soil depth is less than 7.4 m [21], 10 m [22], 12 m [23], 25 m [19], 37 m [24], the side friction has a linear relationship with the depth, which is similar to that in this paper when the soil depth is less than 7.1 m.

With the continuous sinking of the open caisson, the side friction increases. When the open caisson sinks suddenly or deviates, the side friction will change suddenly. For example, when the open caisson sinks to the depth of 5.4 m, the side friction changes suddenly, the open caisson sinks to one side of points B and C, the side friction at point C decreases from 56 kPa to 35 kPa, and the side friction at other points continues to increase. When the open caisson sinks to 12–15 m, due to the continuous deflection of the open caisson to the side of points B and C, the side friction at point A decreases continuously, sinks from the highest 80 kPa to 30 kPa, and the side friction at points B and C increases continuously.

The maximum value of side friction occurs when the sinking depth is 25 m, and the side friction is 170 kPa. When the buried depth reaches 25/32 (about 2/3) times the buried depth of the open caisson, the side wall friction of the open caisson reaches the peak value. As with reference [25], when the buried depth is 2/3 times the buried depth of the open caisson, the side wall friction of the open caisson reaches the peak value.

Take the average value of side friction resistance of each measured point at the same buried depth as the side friction resistance of the soil layer, as shown in Figure 12. Due to the small penetration depth of the open caisson, the side friction of the clay layer, silt containing silt layer, and silt containing silt layer increases linearly and begins to decrease when sinking to the silt soil layer. The side friction of the same soil layer takes the average value, as shown in Table 5.

(2) Analysis of Measured Law of Side Friction at Different Buried Depths. Take the data measured by the soil pressure sensor on the side wall of the open caisson, and analyze the variation curve of side friction at different buried depths, as shown in Figure 13.

It can be seen from Figure 13 that the measured side friction on-site is much greater than that calculated in the specification. In the field measurement, the peak value of side friction increases with the increase of soil depth, and the corresponding buried depth increases. Under the condition of different embedment depth of the same section, the amplitude of the increase of side friction remains basically unchanged. After reaching the peak value, the side friction began to decrease, and the decreasing amplitude was basically the same. The peak value of side friction decreased in steps with the buried depth. The fitting curve of the peak value of side friction at different embedment depths is shown in Figure 14.

It can be seen from the binomial fitting curve that the side friction changes linearly in the early stage of sinking, and the critical depth of side friction is 7.4 m. With the continuous increase of the sinking depth of the open caisson, the peak value of the side wall friction of the open caisson basically increases linearly, and the position of the peak value gradually moves down and presents a quadratic parabola relationship.


4.1. Establishment of Finite Element Model

4.1.1. Model Scheme and Simulated Working Conditions. In order to compare with the field measured data, the model is established based on the field’s actual working conditions.
and formation conditions, and the circular open caisson model is established by using the three-dimensional element of ABAQUS [26] software. Combined with the on-site construction scheme, this paper selects the open caisson for numerical simulation under six different working conditions which are heightening and sinking, and drainage and nondrainage. The total height of open caisson sinking is 32.42 m. When sinking to 30.42 m, open caisson underwater bottom sealing operation is adopted. Each working condition is shown in Table 6.

4.1.2. Model Establishment, Size Selection, and Mesh Generation

(1) Model Establishment and Size Selection. In this paper, the simulation needs to establish four components which are soil, some excavated soil, open caisson, and cross beam. Considering the boundary effect of soil finite element simulation and its influence on the surrounding soil, the length and width of the soil are 100 m. According to the geological survey report, the pebble layer is below the depth of 48.6 m, so the depth of simulated soil is 50 m. Because the circular caisson and the simulated components are symmetrical, in order to speed up the analysis speed and accuracy, 1/4 models are used to simulate in the modeling. 1/4 model is shown in Figure 15(a).

(2) Mesh Generation and Validation. Generally, the finer the mesh is divided, the higher the accuracy of calculation will be, but at the same time, the scale of calculation will also increase, so it is necessary to weigh the two parameters of calculation accuracy and calculation scale.

In order to ensure the accuracy and accuracy of the calculation, the eight-node linear hexahedron element, referred to as c3d8r element, is selected as a whole in the meshing of this model. When meshing the soil, we pay special attention to the accuracy of meshing around the open caisson and at the bottom of the open caisson. The outermost periphery of the soil mass is divided according to the size of 5 m, and the mesh is subdivided in a rectangle of 25*25*50 m with the center of the open caisson as the origin. Taking condition 5 as an example, the horizontal direction adopts single precision division according to the number of units, with the number of units being 15 and the eccentricity being 5. The closer to the center of the open caisson, the greater the density of the mesh, the smaller the distance, the minimum being 0.34 m, and the maximum being 1.7 m. In the vertical direction, it is divided according to the size, and the size is 1 m. When meshing the open caisson, the overall size is 0.5 m, and it is divided by 0.25 m at the bottom of the blade foot and the inclined plane. The size of cross beam grid division is 0.25 m, and the size of excavated soil grid is divided by 1 m. The whole model is divided into 98264 units and 111594 grids. The grid division is shown in Figure 15(b).

4.1.3. Determination of Material Properties. According to the geological survey report and the actual situation of modeling, the soil is divided into five layers, and they are sludge mixed with silt, silt containing sludge, sludge, muddy clay, and pebble. According to the properties of each soil layer, Mohr-Coulomb is selected as the constitutive model. Each soil layer is assumed to be a homogeneous and isotropic linear elastomer. The specific parameters of the soil layer are shown in Table 7.
Figure 11: Continued.
The concrete grade of caisson wall, bottom plate, and cross beam is C40, and the impermeability grade is P12. The main structural material of caisson is assumed to be homogeneous and isotropic linear elastic material. The specific parameters of concrete are shown in Table 8.

### 4.2. Finite Element Numerical Analysis Results

#### 4.2.1. Analysis of the Results of Soil Pressure at the Edge and Foot of Open Caisson

Along the center position path of 1/4 (i.e., 90°) circular open caisson blade foot surface and blade foot inclined plane, the starting point and ending point are the blade foot cross beam position.

**Blade Soil Pressure.** Under different working conditions, the soil pressure change curve at the foot pedal position of the open caisson edge is shown in Figures 16 and 17.

It can be seen from Figure 16 that the soil pressure on the blade tread at the distance of 0 m increases with the increase of the soil penetration depth, and the soil pressure at the tread changes in a wavy manner. At the center of 1/8 circular open caisson, the soil pressure increases with the increase of sinking depth. At the distance of 2.56 m, the soil pressure on the tread of open caisson increases first and then decreases, but the amplitude of change is small relative to the 1/8 position, and gradually changes from the peak position to the trough position.

---

![Figure 11](image.png)

**Figure 11:** Variation curves of lateral friction at different buried depths. (a) Buried depth of 32 m. (b) Buried depth of 31.5 m. (c) Buried depth of 26.9 m. (d) Buried depth of 22.2 m. (e) Buried depth of 17.5 m. (f) Buried depth of 12.8 m. (g) Buried depth of 8.1 m. (h) Buried depth of 3.4 m.
It can be seen from Figure 17 that the soil pressure on the blade tread surface at the distance of 0 m increases with the increase of soil penetration depth. At the position of about 1/8, the soil pressure on the blade tread surface gradually changes from trough to peak with the increase of soil penetration depth, and the growth rate is greater than that in other positions.
y = Intercept + B1*x + B2x

Polynomial fitting lateral friction resistance

Figure 14: Fitted curve of lateral friction peak.

Table 6: Numerical simulation of different operating conditions.

<table>
<thead>
<tr>
<th>Number</th>
<th>Working conditions</th>
<th>Drainage/nondrainage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The first grounding height is 18.47 m</td>
<td>Drainage</td>
</tr>
<tr>
<td>2</td>
<td>The first subsidence is 4.5 m</td>
<td>Drainage</td>
</tr>
<tr>
<td>3</td>
<td>The second sinking to 14.5 m</td>
<td>Drainage</td>
</tr>
<tr>
<td>4</td>
<td>The second grounding height is 11.95 m</td>
<td>Nondrainage</td>
</tr>
<tr>
<td>5</td>
<td>The third sinking to 22 m</td>
<td>Nondrainage</td>
</tr>
<tr>
<td>6</td>
<td>The fourth sinking to 30.42 m</td>
<td>Nondrainage</td>
</tr>
</tbody>
</table>

Figure 15: Finite element model. (a) 1/4 model. (b) Meshing.

Table 7: Parameters of the numerical simulation soil layer.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Density (kg/m³)</th>
<th>Modulus of elasticity (MPa)</th>
<th>Poisson’s ratio</th>
<th>Internal friction angle ($\phi'$)</th>
<th>Cohesion (c/kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge mixed with silt</td>
<td>1720</td>
<td>2.39</td>
<td>0.3</td>
<td>8.7</td>
<td>5.6</td>
</tr>
<tr>
<td>Silt containing sludge</td>
<td>1890</td>
<td>6.81</td>
<td>0.25</td>
<td>17.3</td>
<td>9.1</td>
</tr>
<tr>
<td>Sludge</td>
<td>1710</td>
<td>3.26</td>
<td>0.35</td>
<td>15.3</td>
<td>10</td>
</tr>
<tr>
<td>Muddy clay</td>
<td>1750</td>
<td>3.41</td>
<td>0.36</td>
<td>21.4</td>
<td>10.5</td>
</tr>
<tr>
<td>Pebble</td>
<td>2230</td>
<td>30</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
The variation curves of soil pressure at the inclined plane of the edge foot of the open caisson under different working conditions are shown in Figures 18 and 19.

It can be seen from Figure 18 that the overall soil pressure on the slope of the drainage sinking blade foot decreases first, then increases, then decreases, and then increases in a wavy trend. With the increase of the penetration depth, the soil pressure on the slope at the same position increases continuously. At the same time, with the increase of the penetration depth, the soil pressure at the slope of 1/4 blade foot increases faster than that at 1/8 position.

In Figure 19, nondrained sinking is adopted. The soil pressure increases with the increase of soil penetration depth at the position of 0 m near the position of 4.91 m, and the soil pressure at the slope of 1/4 blade foot increases faster than that at 1/8 position.

(2) Soil Pressure of Blade Foot Slope. The variation curves of soil pressure at the inclined plane of the edge foot of the open caisson under different working conditions are shown in Figures 18 and 19.

It can be seen from Figure 18 that the overall soil pressure on the slope of the drainage sinking blade foot decreases first, then increases, then decreases, and then increases in a wavy trend. With the increase of the penetration depth, the soil pressure on the slope at the same position increases continuously. At the same time, with the increase of the penetration depth, the soil pressure at the slope of 1/4 blade foot increases faster than that at 1/8 position.

In Figure 19, nondrained sinking is adopted. The soil pressure increases with the increase of soil penetration depth at the position of 0 m near the position of 4.91 m, and the soil pressure at the slope of 1/4 blade foot increases faster than that at 1/8 position.

---

**Table 8: Concrete material parameters.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson’s ratio</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>33</td>
<td>0.2</td>
<td>2500</td>
</tr>
</tbody>
</table>

---

**Figure 16:** Soil pressure on the surface of drainage sinking blade foot. (a) Working condition 1: connection height is 18.47 m. (b) Working condition 2: sinking 4.5 m. (c) Working condition 3: sinking 14.5 m.
pressure on the slope of the blade foot increases slightly and gradually decreases from the peak position to the trough position.

According to the drainage and nondrained sinking of open caisson, it can be found that the soil pressure on the foot surface and inclined surface of open caisson increases with the increase of soil depth. The 1/8 position of the foot surface of the drainage sinking blade gradually forms the wave crest with the increase of the soil penetration depth, and the change law of the foot surface of the blade is similar to that of the inclined surface of the foot. The main reason can be explained as follows: when the blade foot slope sinks by the nondrained method, the soil at the blade foot slope plays a smaller role than the blade foot slope.

4.2.2. Analysis of Soil Pressure Results of Side Wall of Open Caisson. Take the 1/4 section of the outer wall of the circular open caisson, divide six paths path 1–path 6 along the side of the open caisson, and analyze the distribution of soil pressure on the side wall of the open caisson under different working conditions, and the position relationship of each path on the contact surface between the side wall and the soil is shown in Figure 20.

The variation law of soil pressure on the side wall of open caisson with depth obtained along paths 1–6 in Figure 20 under working conditions 1–3 is shown in Figure 21.

It can be seen from Figure 21 that the change trend of the soil pressure on the side wall of the open caisson under different working conditions is highly consistent, mainly
showing the change trend of increasing first and then decreasing. Among them, the soil pressure on the side wall decreases rapidly when the path depth from path 1 to path 3 is 13.47 m and increases rapidly when the path depth is 14.97 m. It can be seen from the structural diagram of the open caisson that 13.47–14.97 m is at the cross beam position on the side wall of the open caisson. The stress concentration phenomenon is wired at the upper and lower parts of the cross beam, and the stress relaxation occurs in the middle of the cross beam, resulting in the rapid rise of the side wall soil pressure at 14.97 m. Especially in working condition 2, when the cross beam on the inner wall of the open caisson is just buried, the side wall soil pressure fluctuates the most. The drainage method is adopted to sink the circular open caisson. The depth affected by the cross beam is about 11.74 m, and the width is about 3 m. The soil pressure at the bottom of the side wall of the open caisson increases with the increase of the depth of the open caisson, which is consistent with the variation law of the soil pressure at the bottom of the blade foot measured on-site. The soil pressure on the side wall of open caisson under path 4–path 6 is less affected by the phenomenon of stress concentration and reaches the peak when the depth reaches about 16.69 m, accounting for about 9/10 of the total depth.

The variation law of soil pressure on the side wall of open caisson with depth obtained along paths 1–6 in Figure 20 under working conditions 4–6 is shown in Figure 22.

In Figure 22, the nondrained method is adopted for sinking, and in Figure 22(a), the caisson has not sunk after heightening, and the soil pressure on the side wall shows a
similar change law with the first caisson sinking. Figures 22(b) and 22(c) show a similar variation law, showing a decreasing trend when the soil depth is 13.11 m. After the soil depth is 13.11 m, the side wall soil pressure in working condition 5 increases with the increase of soil depth, and the side wall soil pressure in working condition 6 begins to decrease when reaching the peak value of side wall soil pressure. Working conditions 5 and 6 are affected by the stress concentration at the cross beam on the inner wall of open caisson. However, it has little influence on the range and value of side wall soil pressure, which shows that the drainage method can reduce the stress concentration of the cross beam on the inner wall of open caisson. Taking the open caisson in condition 6 as an example, when the open caisson finally sinks to 30.42 m, the soil pressure reaches the maximum, which accounts for about 2/3 of the total sinking depth, which is basically consistent with the variation law of the field measured results. This phenomenon can be explained by the stress relaxation of the blade foot.

4.2.3. Analysis of Lateral Friction Resistance of Open Caisson. The distribution and variation law of lateral friction resistance obtained from working conditions 1–3 along path 1~path 6 in Figure 20 are shown in Figure 23.

It can be seen from Figure 23 that in working conditions 1–3, the lateral friction resistance increases linearly with the soil depth in the early stage of subsidence. In path 1 and path

![Figure 19: Soil pressure on nondrained blade foot slope. (a) Working condition 4: the connection height is 11.95 m. (b) Working condition 5: sinking 22 m. (c) Working condition 6: sinking 30.42 m.](image-url)
2, the position of the cross beam corresponding to the side wall of the open caisson fluctuates greatly. The reason is that the edge foot of the open caisson and the side wall of the open caisson will be deformed during the sinking process. Because the cross beam on the inner wall of the open caisson plays a supporting role, the deformation of the side wall is small. At this time, it bears the upward resistance of the side wall of the open caisson, and the side friction increases sharply. The soil pressure on the side wall at the position where the lower part of the open caisson does not contact the cross beam begins to decrease. With the increase of soil depth, the phenomenon of sharp increase of lateral friction resistance decreases gradually, increases with the increase of soil depth, and begins to decrease after reaching the peak value of lateral friction resistance. After the first sinking of the open caisson, the lateral friction resistance of the open caisson along path 6 reaches the peak value of 149.86 kPa when the depth reaches 17.13 m, and the peak value of lateral friction resistance increases along path 1∼path 6.

In Figure 24, it can be seen from figure (a) that the lateral friction resistance of the open caisson increases linearly before the end of the first sinking and increases sharply after the completion of heightening. The reason is that after the end of the first sinking and the completion of the second section of open caisson heightening, the soil pressure on the side wall does not play a role due to the rapid increase of the dead weight of the open caisson. It is mainly borne by the bottom resistance and side friction of open caisson. As shown in figure (b), when the open caisson sinks to 22 m, the lateral friction resistance increases linearly after the first sinking, and the height of the open caisson has little effect on the lateral friction resistance of the open caisson. As shown in figure (c), when the open caisson sinks to the design elevation of 30.42 m, the lateral friction resistance begins to decline after reaching the peak value, which is quite different from the situation that the back friction resistance of the open caisson remains unchanged with the penetration of more than 5 m in the existing specifications. The reason is that the resistance of the open caisson is mainly the resistance at the bottom of the blade foot and the inclined plane and the lateral friction resistance of the shaft wall and the upward buoyancy. When the sinking depth of the open caisson is small, the side friction mainly bears the upward resistance. When the sinking depth of the open caisson increases, the resistance and upward buoyancy at the bottom of the open caisson increase, while the lateral friction resistance decreases. Figures (b) and (c) are also affected by the stress concentration of the cross beam of the open caisson, but the influence range gradually decreases with the increase of the soil depth. Under condition 6, the peak value reaches 263.36 kPa when the sinking depth is 25.92 m, and the final lateral friction resistance value is about 73% of its peak value (Figure 25).

4.2.4. Analysis of Stress Results of Open Caisson Cutting Edge Foot Analysis of Stress Results of Open Caisson Cutting Edge Foot. Under working conditions 1∼3, the stress changes of the bottom surface and inclined plane of the open caisson along the 1/4 circular path are shown in Figure 26.
As can be seen from Figure 26, first, the maximum stress of working conditions 1~3 occurs at the intersection of the slope of the blade foot and the bottom of the blade foot, the path is path 5, the stress concentration occurs at the beginning, middle, and end of the path, and the minimum stress occurs at the position 2.5 m from the beginning and 7.7 m from the end of the path. Second, the closer to the intersection between the bottom of the blade foot and the inclined plane, that is, path 5, the more concentrated the stress is. Third, the stress of the intersection between the blade foot slope and the bottom of the blade foot shows a decreasing trend towards the outside of the bottom of the blade foot and the upward direction of the blade foot slope, and under the condition of equal distance from the blade foot interface, the stress of the blade foot slope is greater than the stress of the bottom of the blade foot. Finally, the peak value of stress concentration point decreases with the increase of depth.
Working conditions 4–6 are nondrained sinking. Working condition 4 is the stress change at the bottom of the blade foot when the second pouring is completed and not sinking. The maximum stress occurs in the middle of the path, and the stress at the beginning and end of the path is less than the middle position. The stress change under other paths is similar to that under working conditions 1–3.

From Figures 27(b) and 27(c), at the position of edge foot inclined plane path1–path5, the maximum stress is the starting and ending position under path 1, corresponding to the position corresponding to the cross beam on the inner wall of the open caisson. In the depth range of 0~2.5 m and 7.7~10.2 m, the closer to the edge foot inclined plane, the greater the stress value, and the change law between the depth range of 2.5~7.7 m is opposite. The path from path 5 to path 9 is in the depth range of 0~2.5 m and 7.7~10.2 m. First, the closer it is to the blade foot, the smaller the stress value is, and then, the change law between the depth range of 2.5~7.7 m is opposite.

Figure 22: Soil pressure under paths 1–6 in working conditions 4–6. (a) Soil pressure of working condition 4 under paths 1-6. (b) Soil pressure of working condition 5 under paths 1-6. (c) Soil pressure of working condition 6 under paths 1-6.
When the drainage method and the undrained method are used to sink the open caisson, the change of the stress concentration position at the bottom of the blade foot is quite opposite. The reason is that the open caisson is excavated at the bottom of the large pot. Under the drainage condition, with the continuous increase of the excavation depth, the soil squeezing effect at the bottom of the open caisson blade is increasing, and the stress concentration phenomenon will appear at the cross beam position and the middle position of the side wall of the open caisson. Drainage sinking is adopted, and soil is preferentially taken near the bottom of the edge foot of the open caisson. There is a void phenomenon at the edge foot. With the increase of sinking depth, the buoyancy of the edge foot of the open caisson also increases, and the stress of the edge foot decreases.

Figure 23: Lateral friction resistance under paths 1-6 in working conditions 1–3. (a) Lateral friction resistance under paths 1-6 in working condition 1. (b) Lateral friction resistance under paths 1-6 in working condition 2. (c) Lateral friction resistance under paths 1-6 in working condition 3.
4.2.5. Analysis of Soil Settlement around Open Caisson.

The surrounding surface settlement is one of the important contents of open caisson settlement measurement. This time, the surface settlement under 6 different working conditions is simulated and compared with the field measurement. The soil settlement along path 1 under different working conditions is shown in Figures 28–33, where the horizontal distance represents the distance from the center of the open caisson to the model boundary.

In Figure 28, the open caisson does not sink under working condition 1. The soil mass rises continuously within the horizontal distance of 0–5 m, with a maximum of 0.21 m. The soil mass is always sinking within the range of 5–50 m. The maximum settlement occurs at 7.1 m, with a settlement value of 1.22 m, and the minimum settlement at 50 m of the model boundary, with a value of 0.001 m. The range affecting the depth of soil layer is about more than 3 m from underground, and the influence below 3 m is small. It is
Figure 25: Stress path distribution of open caisson blade foot structure.

Figure 26: Continued.

(a) Distance (m) vs. Stress (MPa) for various paths.

(b) Distance (m) vs. Stress (MPa) for various paths.
(c) Figure 26: Structural stress in working conditions 1~3 in path 1-9. (a) Structural stress in working condition 1 under path 1-9. (b) Structural stress in working condition 2 under path 1-9. (c) Structural stress in working condition 3 under path 1-9.

(a) Figure 27: Continued.
Figure 27: Structural stress in working conditions 4–6 in path 1-9. (a) Structural stress in working condition 4 under path 1-9. (b) Structural stress in working condition 5 under path 1-9. (c) Structural stress in working condition 6 under path 1-9.

Figure 28: Soil settlement in path 1 in working condition 1. (a) Stress cloud chart of working condition 1. (b) Settlement curves at different depths.
reasonable to explain that the soil is squeezed within 0~5 m of the open caisson. However, the soil mass at the foot edge is affected by the dead weight of the open caisson, and the settlement is the largest. Except for the soil mass inside the open caisson, the soil mass is in a sinking state as a whole.

In Figure 29, the open caisson sinks 4.5 m under working condition 2. According to the settlement curve, the soil with a depth of 5 m and a horizontal distance of 0~5 m is in a uplift state, and the maximum uplift height is about 0.11 m. The soil subsidence is most obvious at the bottom of the blade foot. When the depth of path 1 is 6 m, the maximum settlement is about −0.32 m. Under working condition 2, the depth of the bottom layer is about 8 m, and the influence below 8 m is small. The surface settlement is the largest near the open caisson, with a value of −0.11 m, and the average overall settlement of soil is about 0.05 m.

In Figure 30, the open caisson sinks 14.5 m under working condition 3. According to the settlement curve, the maximum settlement is about −0.01 m when the surface depth is 0 m. The uplift is most obvious at the center of the open caisson. When the depth is 14.5 m, the soil uplift height is the most obvious, up to 0.24 m. Under the condition of working condition 3, the soil heave occurs within the depth of 14.5~23.5 m, and the influence range is 0~7 m from the horizontal distance. The surface is in a sinking state as a whole, but the sinking depth is small.

In Figure 31, the open caisson is raised to 32.42 m under working condition 4. According to the settlement curve, when the surface depth is 0 m, the maximum settlement near the open caisson is about −0.23 m. Under the action of self-weight, the effect of the open caisson at the bottom of the center of the open caisson is more obvious. When the depth is 15.5 m and the horizontal distance is 7.1 m, the maximum subsidence is −0.53 m. When the sinking height of the open caisson is 32.42 m, the influence depth range is large, and obvious settlement occurs in the depth range of 5~22.5 m.

In Figure 32, under working condition 5, the open caisson sinks to 22 m underground and sinks by nondrained method. According to the settlement curve, when the surface depth is 0 m, the maximum settlement occurs near the open caisson, and the maximum settlement is −0.24 m. Due to the influence of the hydrostatic pressure at the bottom of the open caisson, the maximum soil settlement occurs at the bottom of the center of the open caisson. When the buried depth is 22 m, the maximum settlement depth is −0.45 m. Under working condition 5, the influence of the depth within the range of 0~27 m on the soil settlement is obvious.

In Figure 33, under working condition 6, the open caisson sinks to 30 m and sinks by the nondrained method. According to the settlement curve, when the surface depth is 0 m, the maximum settlement occurs near the open caisson, and the maximum settlement is −0.34 m. The maximum soil settlement occurs at the depth of 30 m, and its value is about −2.80 m. Under working condition 6, the settlement range is larger, and the effect is more obvious in the depth range of 0~40 m.

The comparative analysis of numerical simulation results and field measured results of ground horizontal settlement under 6 working conditions is shown in Figure 34.

It can be seen from Figure 34 that the surface settlement (the depth is 0 m) simulated by finite element decreases with the increase of horizontal distance. The maximum position is on the outer wall of open caisson, and the settlement is 0.27 m. The field measured sinking amount of open caisson basically tends to be stable on the 9th day of sinking, and the final settlement is about 0.24 m.

From the above various working conditions and settlement curves, the settlement law of open caisson in the process of sinking can be summarized as follows:

1. For the settlement under different working conditions, generally speaking, no matter what working conditions, the soil settlement at the bottom of the edge foot of the open caisson is obvious, and the surface soil subsidence occurs. At the initial stage of sinking of the open caisson, the soil at the center point of the circular open caisson is in a uplift state, and the uplift becomes more obvious with the increase of the soil penetration depth. When the height of working condition 4 reaches 32.42 m, the soil uplift at the central point of the open caisson decreases to a negative value. With the increase of the soil penetration depth and the continuous increase of hydrostatic pressure, the soil settlement at the central point becomes larger and larger, reaching the maximum value (−2.8 m) in working condition 6.

2. It can be seen from Figure 34 that under different working conditions, the greater the distance from the side wall of the open caisson, the smaller the surrounding settlement. The maximum settlement under the first three working conditions is about 0.15 m, so the initial settlement has little impact on the surrounding settlement. In the latter three working conditions, the maximum settlement under working condition 6 is about 0.33 m. Under working condition 6, the settlement value is about 0.16 m when it is 10 m away from the side wall of the open caisson, decrease to 0.08 m when it is 20 m away from the side wall of the open caisson, and then 0.02 m when it is 30 m away from the side wall of the open caisson. Therefore, it can be considered that the settlement is small at a distance of 30 m away from the side wall of the open caisson, and the impact of settlement on the surrounding environment can be ignored.

3. Based on the comparative analysis of the final settlement under working condition 6 and the settlement curve varying with time on-site, it can be seen that the field measurement reaches the design elevation after 12 days of settlement, the final surrounding settlement is about 0.24 m, and the numerical analysis result is about 0.27 m. The
Figure 29: Soil settlement in path 1 in working condition 2. (a) Stress cloud chart of working condition 2. (b) Settlement curves at different depths.

Figure 30: Soil settlement in path 1 in working condition 3. (a) Stress cloud chart of working condition 3. (b) Settlement curves at different depths.
Figure 31: Soil settlement in path 1 in working condition 4. (a) Stress cloud chart of working condition 4. (b) Settlement curves at different depths.

Figure 32: Soil settlement in path 1 in working condition 5. (a) Stress cloud chart of working condition 5. (b) Settlement curves at different depths.
Figure 33: Soil settlement in path 1 in working condition 6. (a) Stress cloud chart of working condition 6. (b) Settlement curves at different depths.

Figure 34: Analysis of settlement results. (a) Settlement simulation results under different working conditions. (b) Comparison between settlement simulation results and field results.

5.1. Comparative Analysis of Soil Pressure on Cutting Edge and Pedal Surface. Two typical working conditions are selected for comparative analysis: working condition 3 (after the first sinking of the open caisson, the open caisson is relatively stable, and there is no deflection) and working condition 6 (after the second sinking of the open caisson, the open caisson is relatively stable, and there is no deflection). According to the damage characteristics of the single side blade foot of the open caisson, the symmetrical position of the side wall of the open caisson can be treated as a whole [27], and the open caisson can be regarded as a wedge-shaped foundation, as shown in Figure 35.

The bearing capacity at the end of deep and large open caisson is calculated according to the existing specifications [28–30]. Taking working condition 3 as an example, according to the relevant requirements of code for design of foundation and foundation of railway bridge and culvert (TB 10093-2017), the soil pressure on the edge and foot is calculated, the theoretical calculation value of the soil pressure on the edge and foot is obtained, and the corresponding analysis values in field measurement and numerical simulation are sorted out. The comparative analysis data of soil pressure on the cutting edge and pedal surface are shown in Table 9.

It can be seen from Table 9 that the field measured soil pressure at the blade foot under working condition 3 is small, mainly because the blade foot surface is not fully stressed in the early stage of sinking, and the numerical simulation results are quite different from the theoretical calculation. Under working condition 6, the error between field measurement and numerical simulation results is 14%, and it is obvious that the theoretical calculation results are small.

5.2. Comparative Analysis of Soil Pressure on Blade Foot Slope. In the specification, the calculation formula of blade foot slope resistance is not clearly given. According to the previous research results, the column hole expansion theory [31] can be used for calculation. According to the centrifugal model test, the ratio of the soil resistance of the blade foot surface and the inclined surface of the blade foot per unit width is about 0.8. Using this ratio, the soil pressure of the blade foot surface can be calculated, and the corresponding analysis values in the field measurement and numerical simulation can be sorted out, as shown in Table 10.

It can be seen from Table 10 that the on-site measured results under working condition 3 are consistent with the reasons in Table 9. No comparative analysis will be made here. The error between the theoretical calculation results and the numerical simulation results is 41.7%. Under working condition 6, the error between the field measured results and the numerical simulation results is 14.7%, and the error between the field measured results and the theoretical calculation results is 61.3%. The theoretical calculation results are small.

5.3. Comparative Analysis of Soil Pressure on Side Wall of Open Caisson. Theoretically, the standard value of lateral active soil pressure acting on the caisson wall shall be determined according to the following provisions:

1. For the ground level, the standard value of active soil pressure above the groundwater level shall be calculated according to the following equations:

   \[
   F_{ep,k} = k_a \cdot r_s \cdot z.
   \]  

   where \( F_{ep,k} \) represents standard value of active soil pressure above groundwater level (kN/m²), \( k_a \) represents active soil pressure coefficient, \( \varphi \) represents internal friction angle, \( r_s \) represents gravity of soil (kN/m³), and \( z \) represents depth from ground to calculated section (m).

2. For the ground level, the standard value of active soil pressure below the groundwater level shall be calculated according to the following formula:

   \[
   F'_{ep,k} = k_i r_s z + r'_s Z_w,
   \]  

   where \( F'_{ep,k} \) represents active soil pressure value below groundwater level (kN/m²), \( Z_w \) represents distance from ground to groundwater level (m), \( r'_s \) represents effective gravity of soil below groundwater level. It can be used at 10 kN/m².

3. For the ground level, the standard value of active soil pressure of multilayer soil layer shall be calculated according to the following formula:

   \[
   F'_{epm,k} = k_{an} \sum_{i=1}^{n-1} r_{ai} h_i + k_{an} r_m Z_n - \sum_{i=1}^{n-1} h_i,
   \]  

   where \( F'_{epm,k} \) represents standard value of active soil pressure at \( Z_n \) depth from the ground in the nth soil layer (kN/m²), \( r_{ai} \) represents gravity of soil layer \( i \) (kN/m³), the effective gravity is taken when it is below the groundwater level, \( r_m \) represents gravity of soil layer \( n \) (kN/m³), the effective gravity is taken when it is below the groundwater level, \( h_i \) represents thickness of soil layer \( i \) (m), \( k_{an} \) represents active soil pressure coefficient of soil layer \( n \), and \( Z_n \) represents depth from the ground to the calculation section of the nth soil layer (m).
Theoretically, the standard value of lateral passive soil pressure acting on the caisson wall shall be determined according to the following provisions:

(1) For the ground level, the standard value of passive soil pressure above the groundwater level shall be calculated according to the following equations:

\[ F_{pk} = k_p r_s z, \]  \hspace{1cm} (6)

\[ k_p = \tan^2 \left( 45^\circ + \frac{\phi}{2} \right), \]  \hspace{1cm} (7)

where \( F_{pk} \) represents the standard value of passive soil pressure above groundwater (kN/m³), and \( k_p \) represents the passive soil pressure coefficient.

(2) For the ground level, the standard value of passive soil pressure below the groundwater level shall be calculated according to the following formula:

Sand soil: \( F'_{pk} = k_p [r_s z_w + r'_s (z - z_w)], \)  \hspace{1cm} (8)

where \( F'_{pk} \) represents standard value of passive soil pressure below groundwater level (kN/m²).

(3) For the ground level, the standard value of passive soil pressure of multilayer soil layer shall be calculated according to the following formula:

\[ F_{pn,k} = k_{pn} \sum_{i=1}^{n-1} r_{si} h_i + k_{pn} r_{sn} \left( z_n - \sum_{i=1}^{n-1} h_i \right), \]  \hspace{1cm} (9)

where \( F_{pn,k} \) represents the standard value of passive soil pressure at the depth of Zn from the ground in the nth soil layer (kN/m²), and \( k_{pn} \) represents the passive soil pressure coefficient of soil layer \( n \).

The hydrostatic pressure in the open caisson shall be calculated according to the design water level. The gravity of clean water can be 10 kN/m³, and the gravity of sewage can be 10 kN/m³~10.8 kN/m³ according to the water quality. The theoretically calculated value of the soil pressure on the side wall of the open caisson is taken as the active soil pressure close to the field measured results for comparative analysis, as shown in Table 11.

It can be seen from Table 11 that under working condition 3, the error between theoretical calculation and field measurement results is 16.5%, and the error between theoretical calculation and numerical simulation results is 3.5%. Under working condition 6, the error between theoretical calculation and field measurement results is 10.2%, and the error between theoretical calculation and numerical simulation results is 74.1%. It can be seen from the error results that the error is small when the sinking of the open caisson is shallow, and the results of the three are relatively close. With the increase of the sinking depth, the comparison error of the numerical simulation results gradually increases.

According to the comparison results of soil pressure, the theoretical calculation results are generally small, and the error value gradually increases with the increase of soil depth. The theoretical calculation value is conservative and is no longer suitable for deep and large circular open caisson.
The field measurement and numerical simulation results are close, and the numerical simulation results can provide a reference for construction and design.

5.4. Comparative Analysis of Lateral Friction Resistance.
The standard value of unit side friction on the outside of the vertical shaft wall and the field measured and numerical simulation results are shown in Table 12 with reference to the code for design of reinforced concrete open caisson structure of water supply and drainage engineering cecs137: 2015 [30].

<table>
<thead>
<tr>
<th>Working condition</th>
<th>Theoretical calculation</th>
<th>Field measurement</th>
<th>Numerical simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>15</td>
<td>31.5</td>
<td>34.56</td>
</tr>
<tr>
<td>6</td>
<td>15</td>
<td>79.5</td>
<td>83.24</td>
</tr>
</tbody>
</table>

It can be seen from Table 12 that the field measured results and numerical simulation results under working condition 3 are about twice the theoretical calculation results. Under working condition 6, there is a large deviation between the theoretical calculation results and the field measured results and numerical simulation results, so the application of the specification has certain limitations for deep and large open caisson. Under two different working conditions, the error between the field measured results and numerical simulation results of side friction is less than 10%, and the error is small.

The comparison between the actual value of lateral friction resistance of the same soil layer and the specification is shown in Table 13.

<table>
<thead>
<tr>
<th>Lateral friction resistance</th>
<th>Clay</th>
<th>Sludge with silt</th>
<th>Silt with sludge</th>
<th>Sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of standard side friction</td>
<td>2.91</td>
<td>27.77</td>
<td>76.67</td>
<td>114.35</td>
</tr>
</tbody>
</table>

It can be seen from Table 13 that with the continuous increase of sinking depth, the unit lateral friction resistance increases continuously, and the maximum measured lateral friction resistance is about 7.8 times of the specification. According to the given value of the specification, the open caisson is in a relatively difficult sinking state.

5.5. Comparative Analysis of Field Measurement and Numerical Simulation. For condition 3 and condition 6, the similarities and differences between the field measurement and numerical simulation results can be seen from the above results. For the soil pressure on the blade foot surface and the slope of the blade foot, the error of the field measurement and numerical simulation results under condition 3 is large, while the error of both under condition 6 is small, and the specific value is about 14%. The main reason is that the pedal surface of the blade is not fully stressed in the early stage of sinking, and the numerical simulation results are quite different from the theoretical calculation. For the soil pressure on the side wall of the open caisson, the error between the field measurement and the numerical simulation results under condition 3 is 17.1%, while the error between the two under condition 6 is 48.46%, with a large gap. For the side friction resistance, the field measurement and numerical simulation results under the two working conditions are close, and the error is within 10%.

6. Conclusions
Taking the deep and large circular caisson in the Lucheng District of Wenzhou as the research object, this paper analyzes and studies the deep and large circular caisson’s first sinking and the second sinking after heightening by using the research methods of theoretical calculation, field measurement, and numerical simulation. The following conclusions are obtained:

(1) The sinking of open caisson is not completely uniform and stable but is always in the process of dynamic rocking sinking. At the initial stage of sinking, the quality and height of open caisson are small, and the sinking is easy to control. At the later stage of sinking, the quality of open caisson is large, slender, and large, and the correction is more complex in case of deflection and sudden sinking. It can be reduced by reducing the sinking speed, to control the attitude of the open caisson.

(2) The large-scale finite element software ABAQUS is used to carry out the numerical analysis of the surrounding settlement under the working conditions of deep and large circular construction. The analysis shows that the environmental impact of open caisson construction is small. At the position of 30 m away from the open caisson, the surrounding settlement can be ignored. Compared with the field
measured data of the surrounding settlement of the open caisson, the error is only 11%, which verifies the reliability of the model.

(3) The stress characteristics of the bottom of the blade foot and the inclined plane of the blade foot of the open caisson are very similar, and the soil pressure at the bottom is greatly affected by the attitude of the open caisson. Its variation law is that it increases with the increase of the sinking depth, and it is stable or small fluctuation when reaching the peak. The maximum soil pressure at the bottom of the blade foot is about 5.32 MPa, and the maximum soil pressure at the inclined plane of the blade foot is about 5.16 MPa.

(4) The field measured results of the soil pressure on the side wall of the open caisson have a similar variation law with the numerical simulation results, and the simulation values are also in the same order of magnitude. The specific performance is that the soil pressure on the side wall of the open caisson increases with the increase of the soil penetration depth and begins to decline when reaching the peak value, and the peak position is about 2/3 of the subsidence depth, and the main reason for the subsidence is that when the open caisson is digging and sinking, with the increase of soil depth, the influence of pressure relaxation area on the blade foot is more and more obvious. The value of side wall soil pressure is always between the active soil pressure and the passive soil pressure, and close to the active soil pressure.

(5) The variation of lateral friction resistance of open caisson under different working conditions is similar to the quadratic parabola, which increases first and then decreases. The position of the peak value of lateral friction resistance increases gradually with the increase of depth. There are great differences between the field measurement and numerical simulation results and the existing specifications, which show that the specification values are generally small.

(6) Stress concentration will occur at the bottom of the edge foot of the open caisson corresponding to the cross beam and in the middle of the 1/4 circular open caisson. The combination of the drainage method and the nondrained method can effectively reduce the phenomenon of stress concentration.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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