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Research Article

Field Study on Deformation and Stress Characteristics of Large Open Caisson during Excavation in Deep Marine Soft Clay

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Oujiang River North Estuary Bridge in Wenzhou is the world's first double-deck suspension bridge under construction with three-tower and four-span. It is the first time to build large open caisson foundation in the deep marine soft clay in estuary with strong tide, extending the application scope of caisson. To study the deformation and stress characteristics of large open caisson during excavation and ensure the safety of anchorage excavation, a large number of sensors are arranged in the caisson. By analyzing the change of tip resistance, lateral soil pressure, and posture parameters during caisson excavation, the stress characteristics and deformation of caisson are described. The result shows the following. (1) Because of the thixotropy of soft clay, the reaction force of partition wall in deep soft soil area of caisson is similar to that of blade foot, and the reaction force of blade foot can be effectively reduced through the layering construction of caisson. (2) The height of caisson construction and the sand-bearing stratum will obviously affect the plane torsion angle of caisson. When the caisson enters the sand-bearing stratum, the lateral soil pressure increases significantly, which leads to the increase of the plane torsion angle. (3) The inclination and central deviation of caisson are sensitive to the caisson construction and stratum property. It can be found that the lateral soil pressure, plane torsion angle, inclination, and central deviation of caisson are sensitive to stratum property, and inhomogeneity of stratum easily leads to inclination of caisson. Based on the field monitoring data, the stress characteristics and geometric posture of caisson during sinking are studied, which provide technical guidance for scheme design and subsidence prediction analysis of caisson in deep marine soft clay. It can provide a good opportunity to study the behaviors of large caisson foundation constructed in deep marine soft clay and has great significance and reference value for construction optimization of anchorage structure.

1. Introduction

Caisson foundation is a structure that uses the gravity of the caisson to overcome the side friction and end resistance to sink to the predetermined elevation. It has the characteristics of large depth, high stiffness, good integrity, and large bearing capacity [1, 2]. Therefore, it is widely used in the port terminals, breakwaters, and other structures and is widely used in the main tower or anchorage foundation of large span suspension bridges worldwide [3, 4].

Open caisson needs to pass through multiple heterogeneous soil layers in the process of sinking. The uncertainty and complexity of construction lead to frequent accidents such as deflection, sudden sinking, and sand gushing in construction [5]. In recent years, many studies have investigated the stress characteristics of caisson during excavation [6]. GeuGuwen [7] studied the force of the blade foot during the sinking process through field experiments. Chiou [8] analyzed a laterally loaded bridge caisson foundation in gravel by situ lateral load test. Lai et al. [9] studied the installation mechanism and soil deformation characteristics of GDCO caissons using the 3D large deformation finite-element (LDFE) method performed by the Coupled Eulerian-Lagrangian (CEL) approach.

With the rapid development of caisson foundation to a larger plane and deeper sinking depth, large caissons show different mechanical properties from small- and medium-sized caissons, and there are significant differences in construction technology control and spatial mechanical properties [10–12]. At present, the research results and theories are mostly based on large-diameter pile foundation, which are more suitable for small- and medium-sized caissons. The structure design and construction large open caisson foundation will encounter more and more complex problems, such as the stress of caisson structure, side wall friction, caisson deformation, and abnormal conditions [13, 14].

Due to the poor geological conditions, it is easy to cause safety accidents in the construction process so that the safety of the open caisson excavation is a critical issue for the project [15, 16]. Cases on excavation performance have been reported by many researchers around the world [17–20]. According to the previous research, field monitoring of soil pressure and internal force of structures are essential for engineers to verify the behaviors of the caisson foundation by analytical or numerical approaches [21]. Moreover, it is helpful for construction organizations to reduce the risk, which is vital for the safe and orderly proceed of project.

Most of the existing research studies focus on small and medium size caissons, but few on the resistance of foundation end of large and super large caissons [22]. The side friction plays a leading role during construction in small- and medium-sized caisson foundations, but the stress characteristics of large and super large caisson foundations are much different. Qin et al. [23] pointed out that, with the increase of the plane size of the caisson, the end resistance has gradually become a controlling factor compared with the sidewall friction resistance. At present, the construction of caisson foundation is mainly large and super large caissons. However, the mechanical characteristics of small and medium caissons cannot be applied to large and super large caisson foundations. Zhang et al. [24] proposed an improved soil-water-caisson interaction algorithm with the method of smoothed-particle hydrodynamics (SPH) to realize the simulation of the whole sinking and excavation process of the open caisson. Therefore, combined with the sinking process of large caisson, it is of great engineering significance to study the change law of the end resistance, sidewall friction resistance, and geometric posture of the large and super large caisson in the process of soil extraction [25, 26].

In this study, the south anchorage of Oujiang River North Estuary Bridge is selected as the research object. It is the first time to build large open caisson foundation in the deep marine soft clay in estuary with strong tide so that the study focuses on the deformation and stress characteristics of caisson during excavation; the items are monitored, including the reaction force of partition wall and blade foot, lateral soil pressure, and geometric posture of caisson. This research ensures the safety of excavation project and provides a good opportunity to study the behaviors of large open caisson foundation constructed in deep marine soft clay, and it has important significance and reference value for construction optimization of anchorage structure.

2. Project Descriptions

2.1. Overview. The Oujiang River North Estuary Bridge, located in Wenzhou of Zhejiang, Southeastern China, is a key part of the Ningbo-Dongguan Expressway and the national highway G228, the total length is 2090 m, and the maximum span is 800 m. The main bridge is designed to be a double-deck suspension bridge with three-tower and four-span; the elevation layout of main bridge is shown in Figure 1.

The location of Oujiang River North Estuary Bridge is shown in Figure 2, the north bank of the project is the hills extending east-west, and the south bank is the broad estuarine on Lingkun Island. Combined with the geological investigation, the project can be divided into two landforms: erosion hilly area and accumulation plain area, as shown in Figure 2. The south anchorage is located in the accumulation plain, which is mainly alluvial plain, and the upper layer is marine silt clay. Large caisson foundation design scheme is adopted in the project to meet the basic needs of bridge construction and operation. It is the first time to build large open caisson foundation in the deep marine soft clay in estuary with strong tide.

The south anchorage of Oujiang North Estuary Bridge is gravity anchorage, the foundation adopts the form of caisson structure, and the plane size is 70 m × 63 m. The original top and bottom design elevations of the caisson are +4.0 m and −63.5 m, respectively, and the total height is 67.5 m. Due to the difficulty of final sinking in the late stage of the caisson, after discussion and verification by construction, design, supervision, and experts, the caisson has experienced a design change. The method of advanced final subsidence and base replacement is adopted to increase the bottom sealing thickness and change the bottom design elevation of caisson to −58.5 m. The design of the stepped platform is adopted, the top of south side maintains the original elevation of +4 m, ensuring that the design of anchorage remains unchanged, and the total height is reduced to 62.5 m. The top of north side increases to +9 m, and the total height maintains the original design elevation of 67.5 m. The vertical profile of caisson before and after design change is shown in Figure 3.

2.2. Geological Condition. As shown in Figures 3 and 4, the geological condition of south anchorage is poor. The upper part of the anchorage area is Holocene alluvial or marine silt clay with silt sand and mud, etc., with a thickness of about 33.6 m. Among them, the overlying soft clay is mainly composed of mud layer, with a thickness of about 15 m. It has the characteristics of high compressibility, high water content, high sensitivity, and thixotropy, which are unfavorable to the project. The underlying strata are pebble layer with good engineering properties and serve as the bearing layer of the south anchorage.

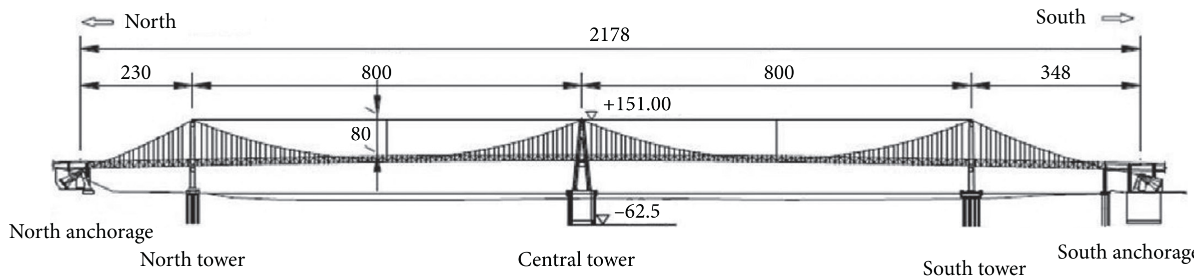

Figure 1: The elevation layout of main bridge (unit: m).

Figure 2: The location of Oujiang River North Estuary Bridge.

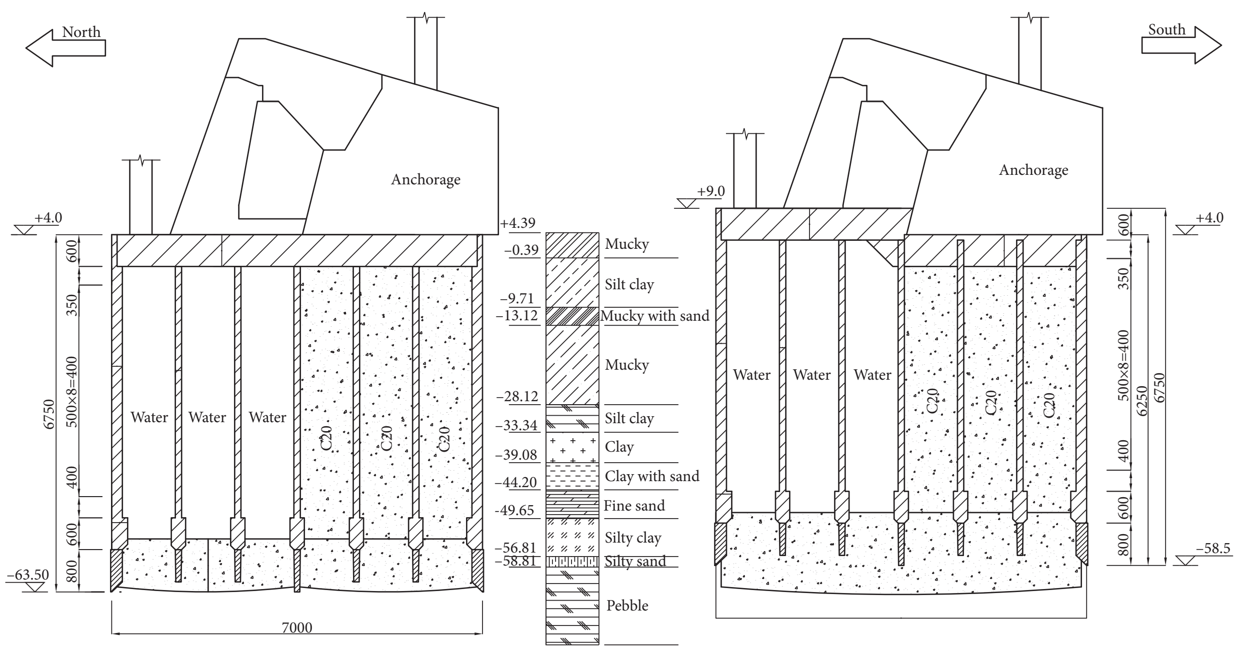

Figure 3: The vertical profile of caisson before and after design change.

As shown in Figure 4, the thickness distribution of the bearing layer is uneven, and the height difference between the north side and the south side of the caisson is 2.47 m. Due to the early final subsidence of the caisson (final subsidence elevation is −58.5 m), the blade foot of the caisson does not enter the bearing layer. In order to ensure the stability of the caisson foundation, the base replacement method is adopted in the construction. The bottom sealing concrete is used to replace the soft soil layer above the pebble layer, and the bottom sealing thickness is increased to make the bottom sealing concrete directly contact with the pebble layer.

2.3. Monitoring Instruments. To monitoring the performance of caisson foundation during the excavation, the GPS monitoring stations are arranged at different positions of the caisson. In the subsidence process of caisson, in order to

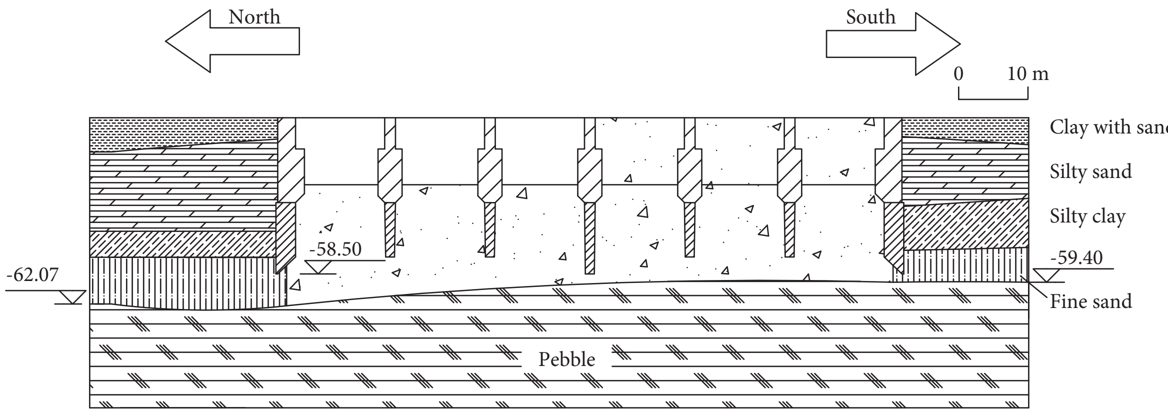

FIGURE 4: The stratigraphic distribution under south anchorage (unit: m).

monitor the geometric posture of caisson in real time and adjust the construction plan timely to ensure the accuracy of the caisson, 4 monitoring stations are arranged at the south anchorage so that the average elevation of caisson, inclination, central deviation, and plane torsion angle can be obtained in the study. The plane position of monitoring gauges is shown in Figure 5.

The sinking resistance of caisson is composed of end resistance, side friction resistance, and buoyancy. The reaction of partition wall and blade foot directly reflects the end resistance during the subsidence process of caisson. The soil pressure on the side wall of caisson is positively correlated with the side friction, and it can also indirectly reflect the change of the side friction. In order to monitor the force condition of caisson during subsidence process and predict the subsequent subsidence process of the caisson, the soil pressure gauges are installed on the side wall and blade foot of caisson. As shown in Figure 6, 17 soil pressure gauges (RF1-RF17) were arranged at the bottom of partition wall and blade foot. 4 measuring points were arranged in each layer of the sidewall soil pressure, and 3 layers were arranged along the height, which were arranged at the height of 4 m, 7 m, and 19 m from the bottom of the caisson. The location of soil pressure gauges is shown in Figures 6 and 7, respectively.

3. Observed Performance of the Caisson during Excavation

The caisson of south anchorage of Oujiang North Estuary Bridge began to be constructed in March 2018, and the end was sealed in March 2020. During the period from March 2018 to January 2020, the geometric posture, end resistance, and lateral soil pressure of caisson were continuously monitored.

3.1. Top Elevation of Caisson. The construction of the south anchorage caisson was divided into three layers, and the heights of each layer are 22.5 m, 15 m, and 25 m, respectively (S1: the sinking process of the first layer; S2: the sinking process of the second layer; S3: the sinking process of the third layer; C2: the construction of the second layer; C3: the construction of the third layer). The change of the average elevation at the bottom of the caisson can be roughly divided into three parts, the sinking process of first layer (S1), the construction and sinking process of second layer (S2+C2), and the construction and sinking process of third layer (S3+C3). As can be seen in Figure 8, the subsidence curve of the first two layers is smooth, indicating that the subsidence process is very smooth, while the subsidence curve of the third layer fluctuates, indicating that the subsidence process is hindered. The installation positions of the monitoring gauges were located at the center point of the four sides of the top of the open caisson, as shown in Figure 5. Therefore, the measurement of the top elevation of the caisson was stopped during the construction process, and the monitoring gauges were rearranged at the new top of the open caisson after the construction completed. Therefore, the variation curve of top elevation shows a zigzag shape.

Combined with geological condition analysis, it can be found that the change of bottom elevation of caisson is related to stratum properties. The south anchorage caisson is located in the deep soft soil so that the excavation process of the first two layers is very smooth. However, during the excavation of third layer of caisson, the caisson sinks to the sand-bearing stratum, and the subsidence process is delayed.

3.2. Reaction Stress on Caisson Tip. The tip resistance can reflect the strength of soil, and its change can represent the subsidence process of south anchorage caisson. As we can see in Figure 6, the monitoring gauges were arranged in partition wall and blade foot. Figure 9 shows the change of blade foot reaction force during caisson excavation, and Figure 10 shows the change of partition wall reaction force during caisson excavation. It can be seen in Figure 9 that the reaction force of blade foot fluctuates greatly. Combined with Figure 8, the change law of blade foot reaction force shows certain correlation with the change of caisson elevation. In the sinking process of caisson, there are five peaks in the reaction force of blade foot. The first three peaks are related to the caisson construction of three layers, and the latter two peaks correspond to the caisson sinking to sand-bearing stratum. Especially in the two peaks of S3, only two points of the cone resistance increased significantly, which

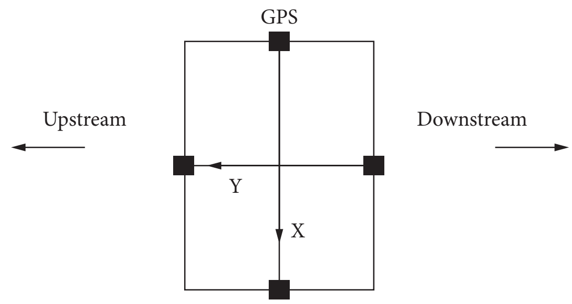

Figure 5: The plane position of monitoring gauges.

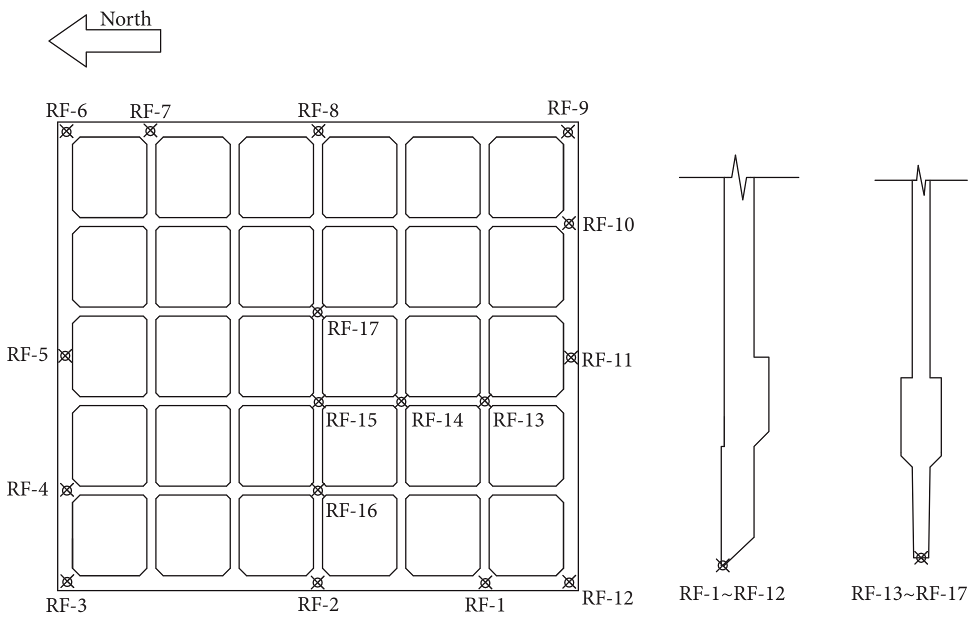

Figure 6: The location of soil pressure gauges on bottom of sidewall and blade foot.

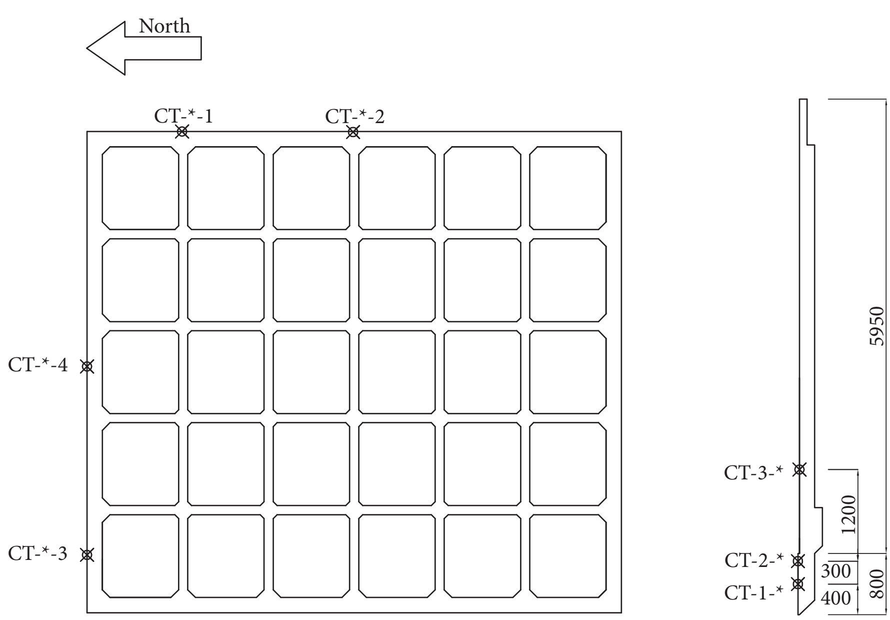

Figure 7: The location of soil pressure gauge on the sidewall (unit: cm).

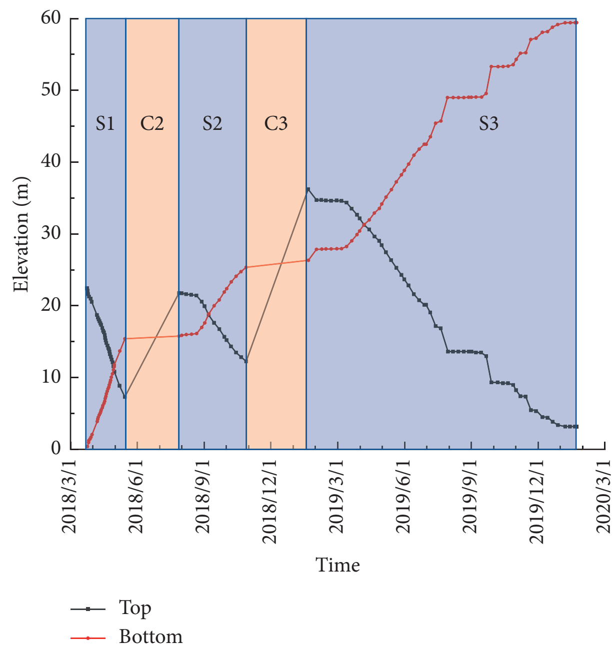

Figure 8: The top elevation of caisson.

indicates that the caisson encountered local obstacles in the process of sinking.

The reaction force of partition wall is not like the blade foot, as shown in Figure 10; the length of central partition wall is larger than the others so that the reaction force of RF-17 is the largest at the beginning of excavation. Since the length of the blade foot of the caisson is longer than that of the partition wall, in the sinking process of the caisson, the blade foot first contacts with the soil; especially when encountering local obstacles, the blade foot undertakes the main bearing work. The partition wall mainly contacts the internal soil of the caisson squeezed by the blade foot, which is generally small and stable. Because of the large deformation of soft soil and the squeezing effect of soil, the reaction force of partition wall in soft soil is greater than that in sand-bearing stratum.

3.3. Lateral Soil Pressure on Caisson. The lateral soil pressure of caisson represents the side friction during the excavation, which can reflect the subsidence condition of caisson just like the tip resistance. Figure 11 is the change of the lateral soil pressure during caisson excavation. It can be seen in the figure that the lateral soil pressure of the caisson is positively correlated with the sinking depth of the caisson, and when the caisson enters the sand-bearing stratum from the soft soil layer, the lateral soil pressure increases significantly. Sand has a larger internal friction angle, so sand has a larger friction resistance than soft clay. With the increase of caisson depth and confining pressure, the growth rate of side friction of caisson in sand stratum is significantly faster than that in soft clay stratum. Especially at the end of the caisson excavation, the lateral soil pressure of caisson increases sharply due to the replacement of soft soil by concrete between the bottom of the caisson and the pebble layer. It can be seen in Figures 9 and 11 that, at the beginning of the sinking of the caisson, the cone end resistance is significantly higher than the side wall friction, which is consistent with the conclusion obtained by Qin et al. [23].

3.4. Geometric Posture of Caisson. The geometric posture of caisson is related to the safety and stability of the south anchorage, which is the focus of the caisson excavation. In this study, the change of geometric posture during caisson excavation is monitored from three aspects: plane torsion angle, inclination, and central deviation. Figure 12 is the change of plane torsion angle during caisson excavation. In this figure, a positive plane torsion angle means the caisson is twisted clockwise, and a negative plane torsion angle means the caisson is twisted counterclockwise. It can be seen from Figure 12 that the plane torsion angle increases obviously after the construction of third layer caisson, while the plane torsion angle changes less after the construction of the second layer caisson. This phenomenon shows that the construction height of caisson has an effect on the plane torsion angle. The larger the construction height is, the larger the torsion angle is. Therefore, in order to avoid the occurrence of large plane torsion angle, the caisson construction with large height should be avoided as far as possible, and in small quantities, many times should be carried out in the construction of caisson. Meanwhile, the occurrence of sand-bearing stratum also makes the plane torsion angle change suddenly. Therefore, the early geological exploration should be done to reduce the accidental increase of plane torsion angle.

Figure 13 is the change of the inclination during caisson excavation. The positive lateral inclination indicates that the caisson inclines to the right (upstream side) of the bridge, and the negative lateral inclination indicates that

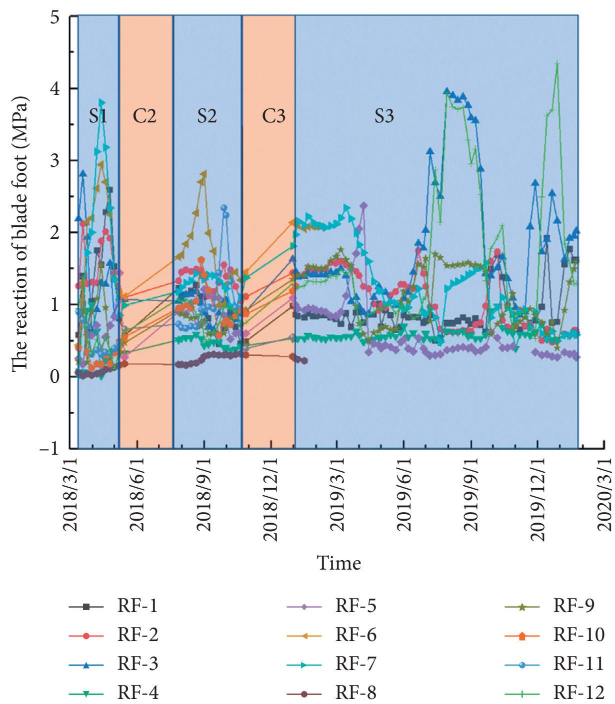

Figure 9: The change of blade foot reaction stress during caisson excavation.

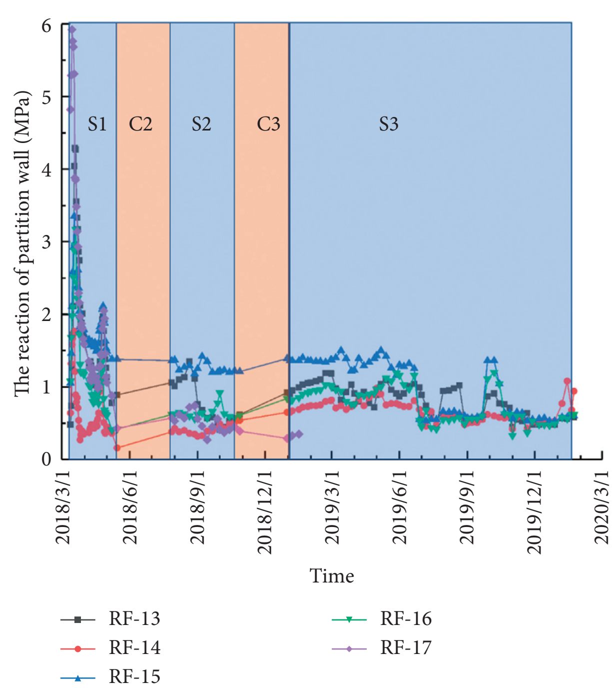

Figure 10: The change of partition wall reaction force during caisson excavation.

the caisson inclines to the left (downstream side) of the bridge. The positive longitudinal inclination indicates that the caisson inclines to the large mileage side (south bank) of the bridge, and the negative longitudinal inclination indicates that the caisson inclines to the small mileage measurement (north bank) of the bridge. It can be seen in the figure that the inclination of caisson is sensitive to the caisson construction. When the caisson construction is completed, the inclination of the caisson changes accordingly, and it is positively correlated with the height of caisson construction. Meanwhile, the caisson sinks smoothly in the soft soil layer because of the thixotropy of

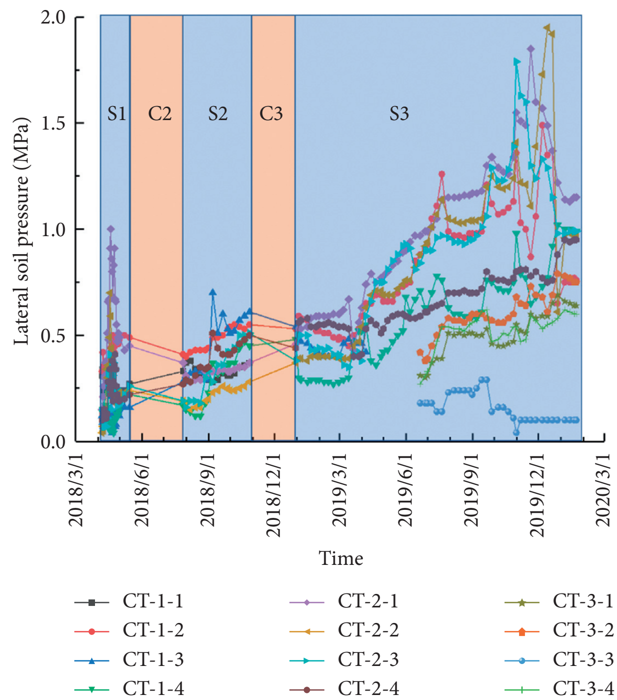

Figure 11: The change of the lateral soil pressure during caisson excavation.

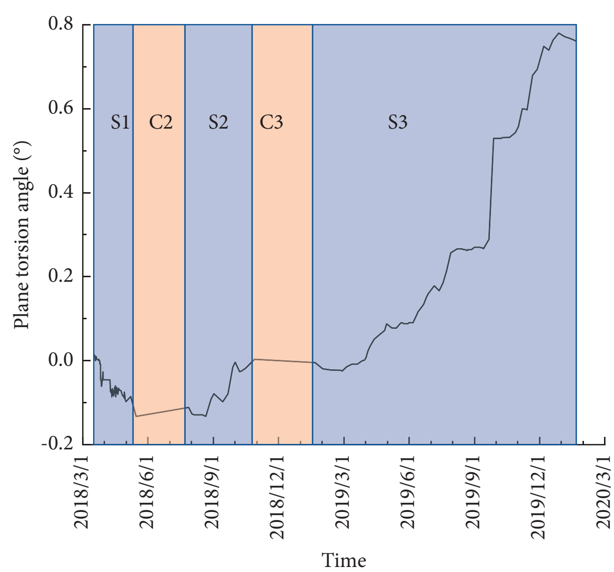

Figure 12: The change of plane torsion angle during caisson excavation.

soft soil. Once it enters the sand-bearing stratum, the caisson inclination begins to change. Especially in September 2019, the lateral inclination changes sharply, which should be paid attention to during the caisson construction.

The change of central deviation during caisson excavation is shown in Figure 14. As same as the change of the inclination during caisson excavation, the change of central deviation during caisson excavation is sensitive to the caisson construction and stratum property. The positive lateral central deviation indicates that the caisson inclines to the right (upstream side) of the bridge, and the negative lateral central deviation indicates that the caisson inclines to the left (downstream side) of the bridge. The positive longitudinal central deviation indicates that the caisson inclines to the large mileage side (south bank) of the bridge, and the negative longitudinal central deviation indicates that the caisson inclines to the small mileage measurement (north bank) of the bridge. It can be seen in the figure that the caisson inclines to the southwest in the construction of second and third layers. When the caisson encounters local

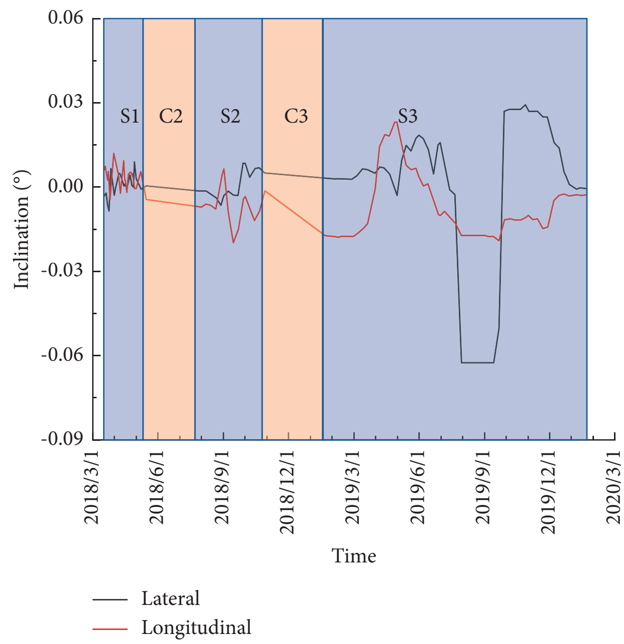

FIGURE 13: The change of the inclination during caisson excavation.

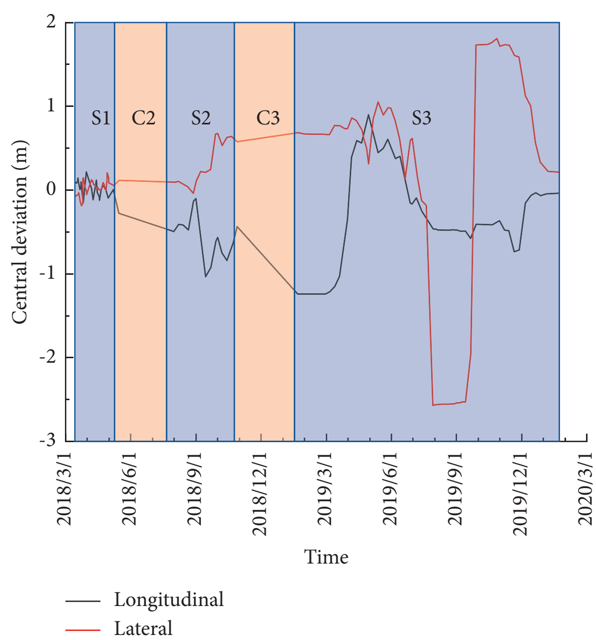

FIGURE 14: The change of central deviation during caisson excavation.

obstacles in the sand layer, the central deviation of the caisson increases significantly, which is consistent with the inclination results.

4. Discussion

Through the comprehensive analysis of the posture and stress characteristics of the caisson, it can be found that the change of the posture and stress characteristics of the caisson in the sinking process corresponds to the change characteristics of the caisson elevation. As we can see in Figure 8, there are 4 platforms in the variation curve of the caisson depth. The first two are due to the layered construction of the caisson, and the last two are due to the obstacles encountered in the sinking of caisson.

According to the monitoring data, the influence of layered construction of open caisson on the posture and stress characteristics during the sinking process of open caisson is analyzed. Through the analysis of cone end resistance, lateral soil pressure, and open caisson posture, it can be found that layered construction of open caisson can effectively reduce the stress concentration at the blade foot.

At the same time, the construction of the second layer and the third layer of the caisson corrects the plane torsion angle, central deviation, and inclination of the caisson, respectively.

As can be seen in figures, it can be found that the inclination, central deviation, and plane torsion angle of the caisson change obviously at October 2019, which are consistent with the obstacles encountered in the sinking process of the caisson. At the same time, the reaction force of blade foot increases significantly. The site construction data show that the caisson encounters the local rocks at this time. Some rocks appear to the west of the southern anchorage, which lead to the end resistance of RF-3 and RF-12 increases significantly. Meanwhile, the whole caisson tilts downstream, resulting in central deviation of the whole caisson, etc. In order to make the caisson sink smoothly, the local rocks are cleaned by the construction organization. Without the support of the rocks, the caisson suddenly sank in September 2019, which makes the monitoring data of the inclination, plane torsion angle, and central deviation have abrupt changes.

Combined with site data, the study suggests that the caisson encounters the soil plugging effect at 2019.10–2019.11. The soil plugging effect is due to the fact that the soil around and at the bottom of the caisson is squeezed into the well to form soil plug during construction and gradually increases with the sinking of the caisson, resulting in the increase of sidewall friction resistance. Since the compression modulus of soft soil is small, the soft soil needs to form a large depth in the open caisson to lead to the occurrence of soil plugging effect. However, the compression modulus of sand-bearing strata is large, so the soil plugging effect will be formed at a small depth, which hinders the sinking of the open caisson.

5. Conclusions

The Oujiang River North Estuary Bridge in Wenzhou is the world's first double-deck suspension bridge under construction with three-tower and four-span; it is the first time to build super large caisson foundation in the deep soft clay in estuary with strong tide, extending the application scope of caisson foundation. In this study, the changes of caisson geometric posture, cone tip resistance, and lateral soil pressure during caisson excavation are studied, which ensures the safety of excavation project and provides a good opportunity to study the behaviors of super large caisson foundation constructed in deep marine clay, and it has important significance and reference value for construction optimization of anchorage structure. Based on the analysis of the field monitoring data, the following conclusions are drawn:

(1) By analyzing the change of cone tip resistance in the process of caisson excavation, it can be found that the layered construction of caisson can effectively reduce the reaction force of blade foot and the probability of stress concentration. And, the reaction force of partition wall in soft soil is greater than that in sand-bearing stratum, due to the large deformation of soft soil and the squeezing effect of soil.

(2) The layered construction of caisson can effectively improve the work efficiency and reduce the stress concentration in the process of sinking. However, the height of caisson construction will obviously affect the plane torsion angle of caisson. Therefore, it is necessary to avoid the excessive height of caisson construction, and the method of a few times should be adopted to ensure the safe subsidence of caisson.

(3) The inclination and central deviation of caisson are sensitive to the caisson construction and stratum property. With the excavation of caisson, the central deviation and inclination in the longitudinal direction decreases gradually, and layered construction of caisson can rectify the deviation effectively.

(4) It can be found that the lateral soil pressure, plane torsion angle, inclination, and central deviation of caisson are sensitive to stratum property; their behavior in the soft soil layer is obviously different from that in sand-bearing sediment. Because of the larger compression modulus, the soil plugging effect may be formed in the sand-bearing strata, and the soil in the caisson should be excavated in time to prevent the formation of soil plugging effect.

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 there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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