Analysis of Stress and Deformation Characteristics of Steel Plate and Steel Pipe Composite Pile Cofferdam

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Abstract. In order to study the stress and deformation characteristics of the PLC construction method pile cofferdam structure, this paper takes the deep-water foundation construction of a certain project as the background. The main bridge of the project adopts (90+180+90) m continuous beam arch, and the lower structure of the main bridge adopts a bearing platform and pile group foundation. The plane size of the cofferdam is 29.8m×22.35m, the overall cofferdam is composed of steel pipe piles, Larsen VI_W shaped steel sheet piles, purlins, and internal supports. Using finite element software to establish a comprehensive model of the cofferdam space, considering the effects of load combinations such as soil pressure, static water pressure, water flow force, and wave force on the cofferdam, it is divided into 5 working conditions for loading calculation according to different construction stages, and the most unfavorable working conditions are obtained. The structural stress and deformation of the cofferdam are analyzed. The results indicate that the strength and deformation of the deep-water foundation cofferdam meet the requirements. The lateral deformation at the center of the cofferdam structure shows a trend of first increasing and then decreasing. For the purlin and internal support system, the force on the lower support is greater than that on the upper support, and the force on the middle position is greater than that on the two ends. To ensure safe construction, the lower purlin and internal support can choose section steel with larger moment of inertia and yield strength.

Keywords: Cofferdam; Steel sheet piles; Deep water foundation; PLC construction method pile; Finite element analysis.

1 Introduction

In the construction of large-span bridges, due to the complex form and high construction difficulty of pier foundations, auxiliary structures are required in deepwater construction. At this time, temporary cofferdams need to be built, and the cofferdam support structure is crucial for the construction of the bearing platform and piers of large-span bridges. Due to adverse weather conditions such as wind, waves, tides, and complex geological conditions, bridge construction faces key technical difficulties such as high construction difficulty and complex working conditions. In recent years, domestic

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and foreign scholars have used numerical simulation and theoretical methods to analyze enclosure structures[1]. Dai Lijun et al. proposed a safety calculation method for steel sheet pile cofferdam based on incremental method[1]. Du Chuang et al. used finite element software to model and analyze steel sheet pile cofferdams[2]. He Ming conducted the design and practice of underwater steel pipe pile cofferdam[3]. Zheng Hong Wu studied the design and construction of the locking steel sheet pile cofferdam on the background of Taizhou Bridge[4].Kimura M et al. explored the design and application of steel sheet piles in structural foundation construction[5]. Osthoff David et al. conducted in-depth research on the deformation behavior of steel sheet piles during jacking construction[6]. At present, the commonly used methods for underwater foundation construction in China include concrete cofferdams, steel box cofferdams, double wall steel cofferdams, and steel sheet pile cofferdams[7]. This article adopts a PLC construction method to form a composite pile steel cofferdam composed of Larsen steel plates and steel pipe piles, and the locking buckles between the steel plate piles and steel pipe piles are welded together for connection. Steel pipe piles mainly serve to resist the soil outside the cofferdam, while steel plate piles and steel pipe piles work together to retain water. Compared with other cofferdams, the advantage of PLC pile cofferdam lies in its green and environmentally friendly features, simple construction, and the ability to effectively shorten the construction period. Compared with other processes, it has outstanding water sealing effects, good water tightness, high support strength.

2 Load Calculation and Working Conditions

2.1 Calculation of Active and Passive Soil Pressure

The main soil in the construction area of the cofferdam project is clay, gravel, the clay layer and gravel are permeable, and the calculation of earth pressure adopts the method of water-soil partitioning, i.e., the floating capacity weight of the soil body is used to calculate the size of the earth pressure of the soil body in the layer. To calculate the soil body the Rankine soil pressure formula is used:

$$\sigma_{ak} = \gamma h_i K_{a,i} - 2c_i\sqrt{K_{a,i}} \tag{1}$$

$$\sigma_{pk} = \gamma h_i K_{p,i} + 2c_i\sqrt{K_{p,i}} \tag{2}$$

2.2 Current Force

PLC method pile steel cofferdam with the same role in the riverbed as the bridge abutment, can refer to the reference[8] in the role of the bridge abutment at the flow pressure calculation method to take the value of the distribution of the flow rate with the depth of the water level increases approximately inverted triangular distribution, so can be obtained directly on the water surface of the flow pressure of the general calculation formula:

$$P = kA\frac{\gamma v^2}{2g} \quad (3)$$

In general, there is flow pressure on the outside of the cofferdam, but the flow pressure on the back water side and the side water surface is small, which is ignored here. From this, it can be calculated that the equivalent concentrated force of the flowing water pressure at the water-facing surface is about 119.79kN, with a distribution set of 2.68kN/m^2.

2.3 Wave Force

When the peaks (valleys) of waves act on the upstream surface of the cofferdam, the cofferdam is subjected to wave forces. The calculation of its acting force is related to wave state, wave elements, water depth, etc.[9]. The wave load acting on the outer side of the cofferdam can be calculated based on the standing wave theory, and the value can be taken by referring to the method in reference9. The distribution diagram of wave force is shown in Figure 1.

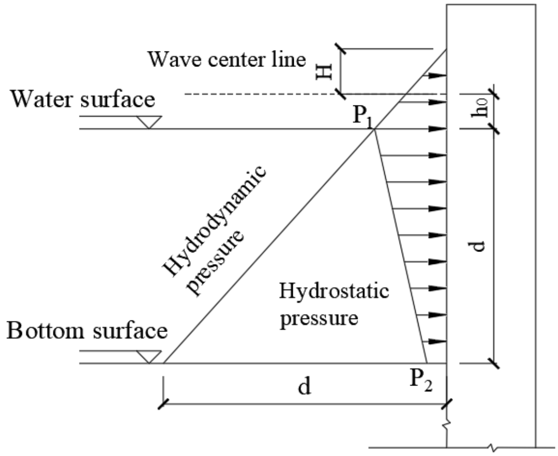

Fig. 1. Schematic diagram of wave loads

Calculate the wave force on the upstream surface of the casing using the Sain-flow empirical formula:

$$P_1 = (P_2 + \gamma d)\frac{H+h_0}{d+H+h_0} \quad (4)$$

$$P_2 = \frac{\gamma}{\cosh\frac{2\pi \cdot d}{L}} = \frac{2\gamma}{e^{\frac{2\pi \cdot d}{L}} + e^{-\frac{2\pi \cdot d}{L}}} \quad (5)$$

$$h_0 = \frac{\pi H^2}{L} \cdot \coth\frac{2\pi \cdot d}{L} = \frac{\pi H^2}{L} \cdot \frac{e^{\frac{2\pi \cdot d}{L}} + e^{-\frac{2\pi \cdot d}{L}}}{e^{\frac{2\pi \cdot d}{L}} - e^{-\frac{2\pi \cdot d}{L}}} \quad (6)$$

In the formula: P_1 is the wave force at the position of the still water surface; Wave force at P_2 water bottom; H is the height of the wave center line; d is the depth of water level; L is the wavelength, according to the Gaillard empirical formula, (9-15) H is taken as 3.6m; H is the height of the wave, taken as 0.3 from hydrological and meteorological data; By substituting known data, it can be concluded that P_1 is 3.28kPa, P_2 is 0.609kPa, and h_0 is 0.078m.

2.4 Construction Steps and Working Conditions

The construction process of PLC construction method pile cofferdam is as follows: after the pile foundation pouring is completed, Larsen steel plate and steel pipe piles are inserted and driven from the upstream side until the cofferdam is closed. Then, the interior of the cofferdam is gradually pumped and excavated, and the fence and internal support are installed at the design elevation position. Then, the bottom concrete is poured to reach the design strength. After reaching the design strength, the construction of the bearing platform and bridge pier is carried out, and finally, the internal support system structure of the cofferdam is removed.

According to the PLC construction method of pile cofferdam construction process, it can be divided into the following 5 working conditions for calculation and analysis: working condition 1, the installation of the first layer of internal support is completed; Working condition 2, the cofferdam is pumped and excavated to +12.93m, and the second layer of internal support is installed; Working condition 3, the cofferdam is pumped and excavated to +9.93m, and the third layer of internal support is installed and completed; Working condition 4, the cofferdam is pumped and excavated to +6.93m, and the fourth layer of internal support is installed; Working condition 5, the cofferdam is pumped and excavated to +3.93m, and the fifth layer of internal support is installed.

3 Numerical Simulation and Force Analysis of Cofferdam

3.1 Cofferdam Modelling

Using Midsa-civil software to establish a spatial overall model of PLC construction method pile cofferdam, and conducting finite element numerical simulation analysis on it. Steel sheet piles are simulated using plate elements, internal supports and purlins are simulated using beam elements, and bottom concrete is simulated using solid elements[10]. The mutual constraint between the cofferdam below the riverbed and the soil layer is simulated using soil springs. The overall spatial model of the cofferdam structure is shown in Figure 2 and Figure 3.

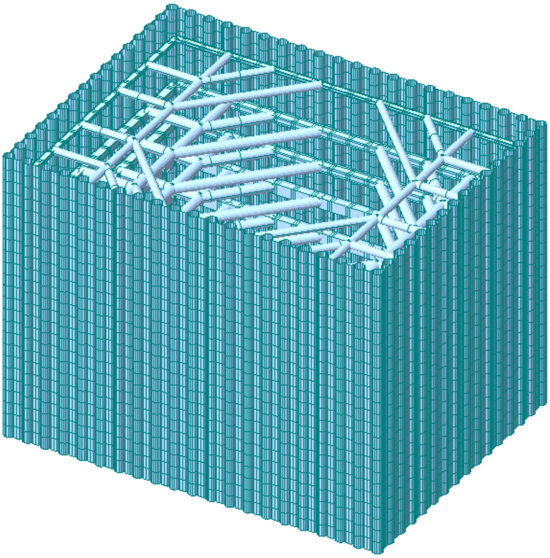

Fig. 2. Overall model of cofferdam

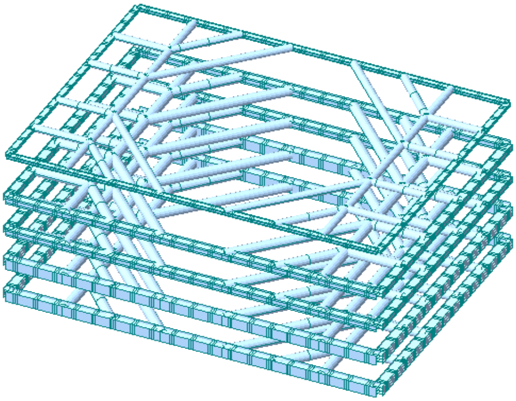

Fig. 3. Internal support model

3.2 Force Analysis of Cofferdam

According to the spatial overall model of PLC pile cofferdam established, five working conditions at different construction stages are analyzed and calculated, and the force diagrams of steel sheet piles and internal support under each working condition are obtained, as shown in Figure 4-9.

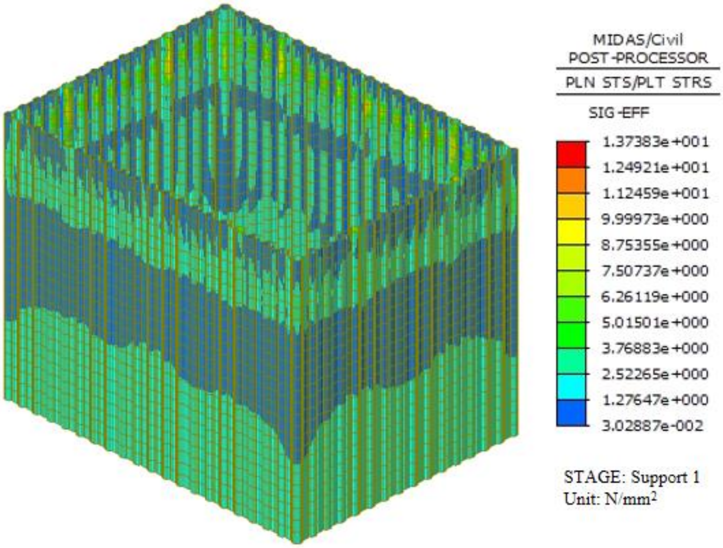

Fig. 4. Stress diagram of working condition 1

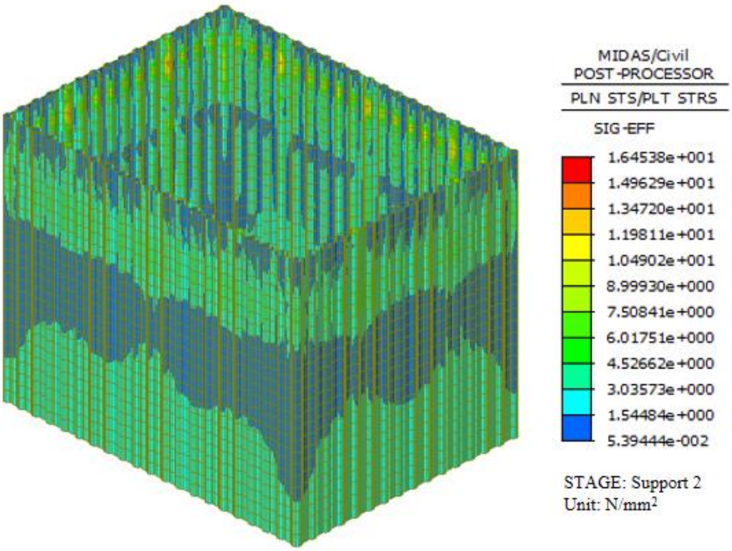

Fig. 5. Stress diagram of working condition 2

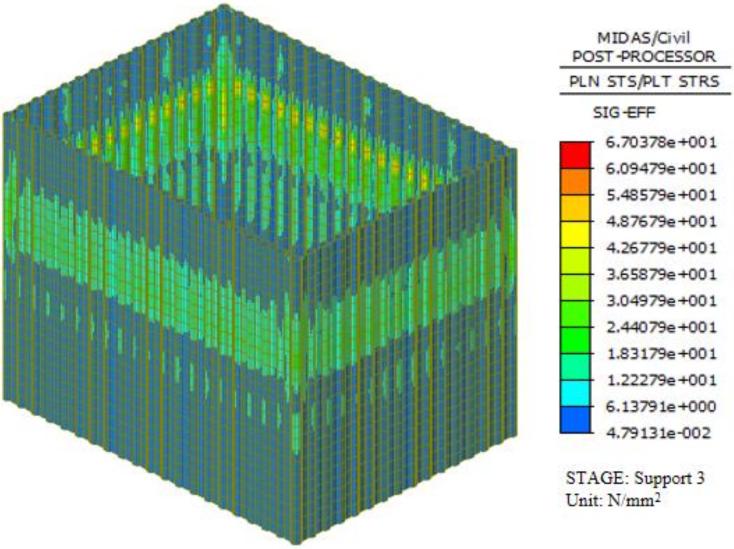

Fig. 6. Stress diagram of working condition 3

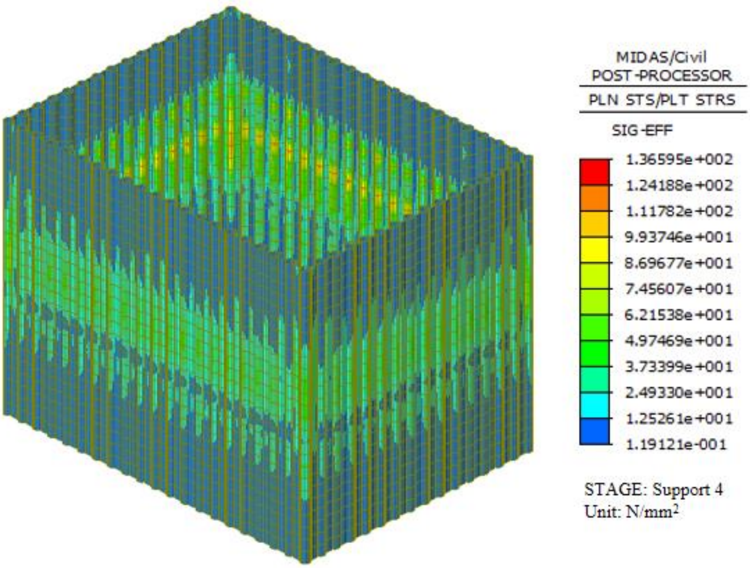

Fig. 7. Stress diagram of working condition 4

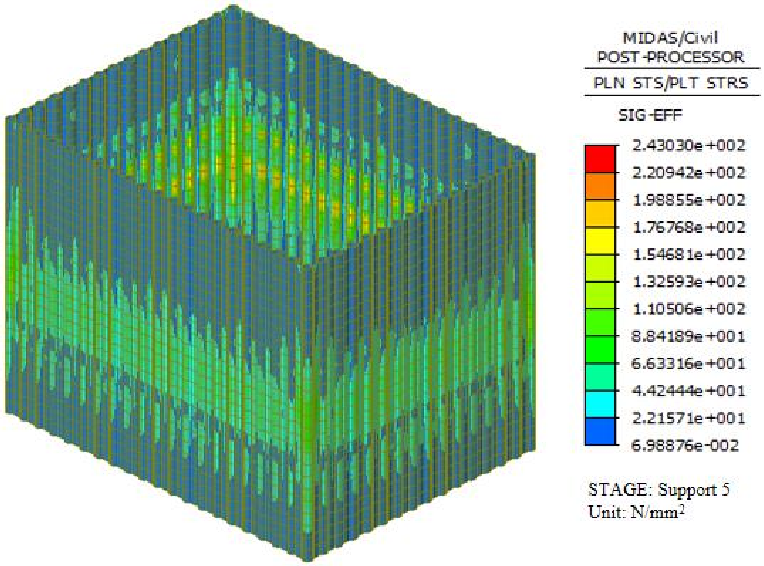

Fig. 8. Stress diagram of working condition 5

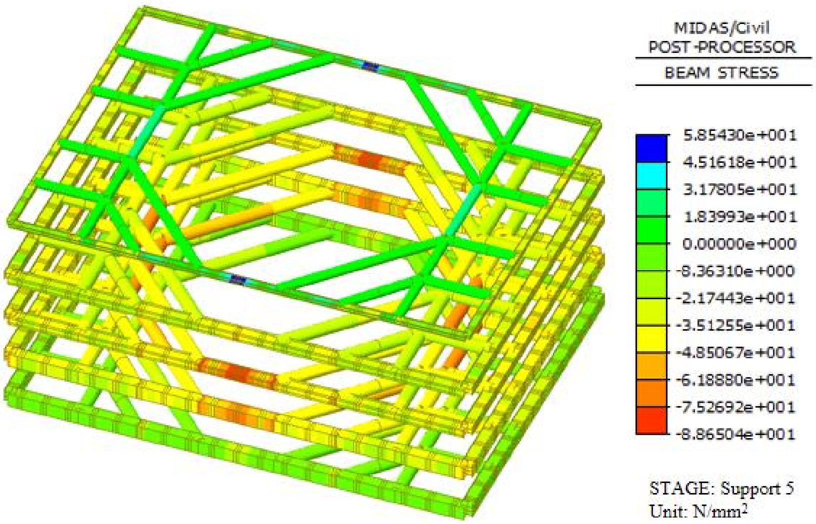

Fig. 9. Purlin and inner support diagram

After modelling and analysis using finite element software, the calculation result for condition 1 was obtained, and the maximum combined stress of the cofferdam was 13.73 MPa; The maximum combined stress of the cofferdam in working condition 2 is 16.64 MPa; The maximum combined stress range of the cofferdam under working condition 3 is between 42.67 and 54.85 MPa; The maximum combined stress range of the cofferdam under working condition 4 is between 99.37 and 111.78 MPa; The maximum combined stress range of the cofferdam under working condition 5 is be-tween 154.68 and 176.76 MPa. The maximum stress of the purlin and internal sup-port is under condition 4, which is 88.65 MPa. In summary, all working conditions meet the requirements, so the cofferdam structure is safe.

The most unfavorable working conditions are working conditions 4 and 5, where the cofferdam is excavated to the elevation of the fourth and fifth layer of the cofferdam and internal support. This is because as the excavation depth increases, the soil and water pressure on the cofferdam gradually increases, resulting in an increase in the combined stress and lateral deformation of the cofferdam. As shown in Figure 9, for the purlin and internal support, the stress on the fourth layer is the highest, and the maximum stress on the longer side of the purlin is greater than the maximum stress on the shorter side. The stress at the middle position of the internal support is greater than the stress at both ends; The stress on the purlins of the 4th and 5th floors is greater than that of the 1-3 floors, which means that the stress in the lower layer is greater than that in the upper layer. The four corners of the cofferdam structure are the weakest points of force, so it is necessary to strengthen the connection at the four corners. For internal support, the force on the lower support is greater than that on the upper support, and the force on the middle support is greater than that on the edge support. To ensure safe construction, nether level purlins and internal supports can be made of steel with larger cross-sectional moment of inertia and yield strength. According to the actual construction situation, steel pipes can be added at the center position of the 4th and 5th floor purlins to avoid instability of the cofferdam.

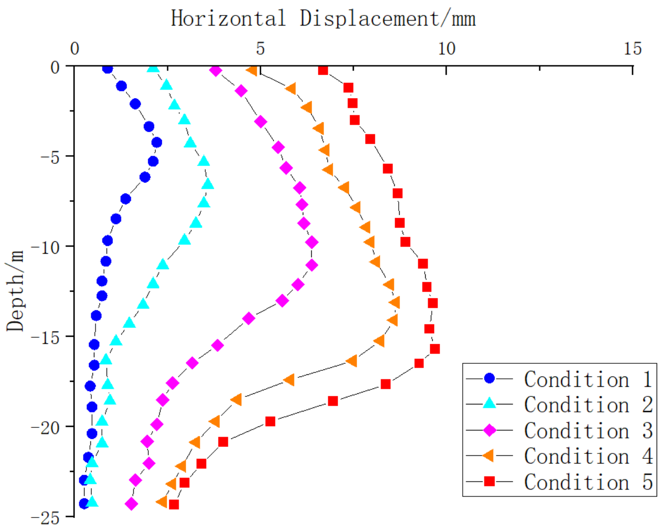

Fig. 10. Short side of cofferdam

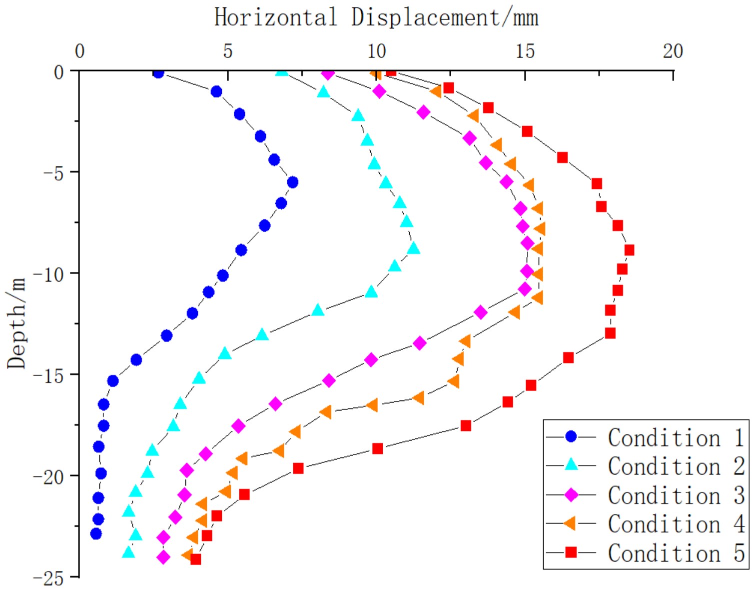

Fig. 11. Long side of the cofferdam

From Figures 10 and 11, it can be seen that the maximum horizontal displacement on the short and long sides of the cofferdam is located at the centerline position. The range of lateral deformation of the cofferdam increases with depth, and the trend of change under different working conditions is basically similar. The displacement of the pile body shows a trend of first increasing and then decreasing from the pile top to the pile end. At a depth of h=-15m, the maximum displacement is manifested, that is, when the construction reaches working condition 5, the excavation inside the cofferdam reaches the bottom, and the maximum load such as soil pressure and water pressure on the cofferdam leads to the maximum deformation. In working condition 1, the displacement of the steel sheet pile at a depth of 15m has approached a certain minimum value, indicating that the main and passive soil pressure values of the soil below the riverbed are relatively small under this working condition; In working conditions 2-5, the displacement of the steel sheet piles tends to stabilize only at depths of 17, 18, 19, and 20 meters, indicating that the main and passive earth pressures of the soil below the riverbed are at a relatively high level. Moreover, as the excavation depth inside the cofferdam increases, the depth corresponding to the stable displacement value gradually.

4 Conclusion

Based on the PLC construction method used in the construction of deep-water foundation for bridge piers, this article uses finite element software to model the overall structure of the cofferdam, analyses the stress and deformation characteristics of the cofferdam under different working conditions, and obtains the following conclusions:

(1) The finite element simulation analysis results show that under the most unfavourable working conditions, the strength and stiffness of Larsen steel plates, steel pipe piles, purlins, and internal supports all meet the structural stress requirements, indicating that the PLC construction method pile design in this project is reasonable.

(2) The development trend of the displacement curve of steel sheet piles along the depth direction under different working conditions is approximately the same, showing a trend of first increasing and then decreasing. The deformation at a certain depth displacement gradually increases with the progress of the construction process, and the maximum displacement change occurs at the end of excavation.

(3) For steel sheet piles, the weakest and most dangerous point of force is at the corner of the steel sheet pile. Therefore, the focus is on strengthening the connection strength at the corners of the cofferdam to avoid potential damage caused by the cofferdam. For internal support, the lower support is subjected to greater force than the upper support, and the middle support is subjected to greater force than the edge support. Therefore, the support below can choose steel with a larger cross-section to prevent danger.

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