Design and Construction of Double-wall Steel Cofferdam in Deep Water Foundations

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Abstract. Deep water foundation is constructed by cofferdam in bridge engineering. Safety, quality, cost, and duration of bridge construction depend on the reasonable and feasible deep water cap cofferdam design and construction scheme. “Pile first, cofferdam back” construction program of double-wall steel cofferdam for deep water cap is applied in second SongHua river bridge. The results show that structural stiffness of steel cofferdam, strength of each component both meet work requirements under the most unfavorable conditions in the life-span of the construction process. This scheme effectively solves the technical difficulties in cofferdam construction and improve the working environment of installation and subsidence process. The project is going on well and the duration of construction time is reduced. This technique serve as a helpful reference to similar engineering.

Key words: Deep water bridge foundation, double-wall steel cofferdam, design, construction technique.

1. Introduction
With the large-scale construction of expressways and railways, more and more super bridges span deep water, which promotes the rapid development of deep water foundation construction technology. The deep-water foundation is generally located in a complex environment with comparative quality conditions. The construction difficulty varies with different regions and projects, and the construction quality is often difficult to control [1]. The main difficulties in the construction of deep-water foundation of bridge lie in, such as, waterproof, anti-soil, anti-scour, anti-skid slope [2-4], the cofferdam can provide a water-free and dry construction environment for the construction of bearing platform by surrounding water with cofferdam wall plate and bottom sealing concrete. The double wall steel cofferdam is a circular double wall fully welded watertight steel structure cylinder with a single inclined edge [5]. It is composed of the middle horizontal and vertical trusses and the bottom edge of the connecting bottom of the inner and outer wall plates. The horizontal and vertical stiffened ribs and the horizontal chord plates are arranged around the wall plates. The angle steel is welded between the inner and outer chord plates on the same plane to connect the inner and outer walls, so that the inner and outer walls are combined into a whole, with self-buoyancy and higher strength double wall steel shell. The compartment plates
are also arranged between the inner and outer walls to divide the whole cofferdam into several parts in order to ensure the stability of the steel cofferdam when it is immersed in the steel shell during the water suspension stage, and to be able to inject water or concrete in different compartments when it is on the river bed, so as to adapt to the height difference of the riverbed surface and adjust the inclination of the cofferdam [6]. As a kind of water retaining structure for foundation construction of deep-water bridge, it has the advantages of structural safety, single working procedure and simple construction. However, in the process of application of double-wall steel cofferdam, the structural design is often unreasonable. The water-proof effect is not desired after the water in the cofferdam is pumped. Meanwhile, the structural strength, rigidity, stability of the cofferdam are usually insufficient [7-9]. So far, the research on the key technology of waterproof cofferdam construction is still a hot spot in the field of engineering construction.

2. Project Overview

Figure 1. Layout of main pier cofferdam (unit: mm except elevation in M)
The second Songhua River Super Bridge is located in the south of the Jiujiang line Songhua River Bridge in the northeast of Jiuzhan station, Longtan District, Jilin City. The bridge crosses the Songhua River in the north-south direction. There are levees on the left bank and mountains and floodplain on the right bank. The distance between the levees and mountains is about 620m. The formation lithology of the bridge site is the fourth quaternary artificial filling soil, plain filling soil and filling soil; quaternary holocene alluvial proluvial fine sand, coarse round gravel soil and pebble soil are combined with Yanshan R52 granite. Within the scope of the project, the construction normal water level is 177.00m, a 20-year flood level is 181.73m, and a 100-year flood level is 183.33m. The highest navigable water level is 181.39m, and the lowest navigable water level is 175.62m. The whole bridge is 861.59m long, with 26 spans in total, of which the 13th-18th span spans the second Songhua River, and the 13th-17th pier pile foundation, bearing platform, and pier body are all in the water. The main bridge foundation adopts bored pile foundation, with 11 φ 1.5m bored piles arranged in three rows along the bridge direction as plum piles. The size of rectangular bearing platform is 14.5m × 9.7M × 3.5m, and the bottom elevation of bearing platform is + 169.19m. Double-wall steel cofferdam construction is adopted for the foundation construction of main pier. Due to the long construction duration and great construction difficulty of the scheme of "weir before pile", large floating boat is required to hoist the steel cofferdam, so the site is limited and it is not easy to control the sinking deviation of cofferdam. Therefore, the method of "pile before weir" is adopted for construction, i.e. 1) foundation cleaning, arranging the dredger to clean up the large stones at the pier position, leveling the foundation and backfilling the river sand; 2) trestle construction and drilling platform; 3) bored pile construction; 4) cofferdam and cushion cap construction.

3. Basic Design Parameters of Double Wall Steel Cofferdam

The full height of the double-wall steel cofferdam is 16m, the wall thickness is 1.2m, the maximum pumping water level is +180.3m, the thickness of the bottom sealing concrete is 2.3m, and the bottom elevation of the cofferdam sunk in place is +165.73m. The specific layout is shown in Figure 1. Due to the long construction period and difficult construction of the scheme of "pile before weir", and the large floating boat is required to hoist the steel cofferdam, so the site is limited, and it is not easy to control the sinking deviation of the cofferdam, the method of "pile before weir" is used for construction, i.e. 1) foundation cleaning, arranging the dredger to clean up the large stones at the pier position, leveling the foundation and backfilling the river sand; 2) trestle construction and drilling operation platform; 3) drilling pile construction; 4) construction of cofferdam and the bearing platform. During the construction of bearing platform, the maximum pumping water level of cofferdam is designed as + 180.3m, the flat area of cofferdam shaft is 68.72m2, the self-weight of cofferdam is 267t, the total weight of 1.3m cutting edge concrete is about 164t, and the self-weight draft of cofferdam is 6.28m. Other basic parameters are shown in Tables 1 and 2.

| Table 1. Parameters of main pier bearing platform |
|-----------------------------------------------|
| Pier No | Cofferdam top | Cofferdam bottom | Bearing platform length | Bearing platform width | Cofferdam length | Cofferdam width | Cofferdam wall thickness |
|--------|--------------|------------------|-------------------------|------------------------|------------------|-----------------|-------------------------|
| Main pier | +181.73m | +165.73m | 14.5m | 9.7m | 17.9m | 13.1m | 1.2m |

| Table 2. Material parameters of main pier cofferdam |
|-----------------------------------------------|
| name | Inner and outer wall plates | Vertical rib | Horizontal ring plate | panel separating one cabin from another | Horizontal truss | Shaft wall concrete | Back cover concrete |
| Specifications | Δ=6mm | ≤75×50×6 | δ=12mm | Δ=14mm | ≤100×10 | C20 | C30 |
4. Calculation of Construction Condition of Double Wall Steel Cofferdam

The main parameters of the double-wall steel cofferdam are the inner wall of the cofferdam to the outer edge of the bearing platform is 100mm, the upper horizontal ring and horizontal truss have three layers, the upper horizontal ring is 12 × 200mm ring plate, the upper horizontal truss is \( \angle \ 75 \times 6 \); the middle horizontal ring and horizontal truss have ten layers, the middle horizontal ring is 12 × 240 + 14 × 150 mm ring plate, the middle horizontal truss is \( \angle \ 100 \times 10 \), the lower horizontal ring and horizontal truss have three layers, and the lower horizontal truss has three layers. The horizontal ring is 12 × 200mm ring plate, the lower horizontal truss is \( \angle \ 75 \times 6 \), the inner and outer side-wall plates of the cofferdam are 6mm, the vertical rib is \( \angle \ 75 \times 50 \times 6 \) angle steel, the spacing is 300mm, the thickness of the partition board is 14mm, and the self-weight of the cofferdam is about 267t. The cofferdam has a wall thickness of 1.2m and a total height of 16m (6 + 5 + 5) m, which is manufactured in three sections. The thickness of the bottom sealing concrete is 2.3m.

(a) computational model  
(b) 12×220+14×150mm Ring plate stress diagram (MPa)  
(c) 12×200mm Ring plate stress diagram (MPa)  
(d) Horizontal truss \( \angle 75 \times 6 \) Axial diagram (kN)
**Figure 2.** Calculation model and results of cofferdam sinking condition

1) Case 1: Cofferdam sinking condition

After the cofferdam is accurately positioned, 7.5m water shall be injected into the cofferdam wall first to make the cofferdam sink to the bottom of the excavation foundation pit. Therefore, the inner wall of the cofferdam shall bear the water pressure generated by 7.5m water in the wall. The total weight of the cofferdam is balanced by the buoyancy provided by the shaft wall of the cofferdam, and the outer wall of the cofferdam bears the water pressure generated by the self-weight draft of the cofferdam and the inner wall. After the cofferdam bed is stable, the construction in the cofferdam shaft wall is filled with concrete, the mud is sucked in the cofferdam, and the cofferdam is sunk to the design elevation. The total draft of the cofferdam is 13.7m. The flow force is calculated according to the code of Load for Port Engineering:

\[ R = C_w \frac{r V^2}{2g} A \]  \hspace{1cm} (1)

Where \( C_w \) is the flow resistance coefficient (\( C_w = 1.45 \)), \( r \) is the bulk density of water, \( V \) is the water velocity (\( V = 3.0 \text{ m/s} \)), \( g \) is the acceleration of gravity, and \( A \) is the projection area of the water entering part of a single pile perpendicular to the flow direction.

The force point of water pressure resultant force is 0.3 times of water depth below the design water level. The result of the flow force \( R = 1607 \text{kN} \).

The model is constructed by Midas 2006. The horizontal ring plate is the beam element, the horizontal angle steel is the truss element, the wall plate is the ribbed thin plate element, the compartment plate is the thin plate element, and the internal support is the beam element. As the cofferdam is a symmetrical structure, vertical constraints are added to the inner and outer wall plate joints at the bottom of the cofferdam, and horizontal constraints are added to the inner and outer wall plate joints at the symmetrical position of the cofferdam bottom. The type of water pressure load is fluid pressure load. The calculation model and results are shown in Figure 2.

During the cofferdam construction, the maximum water pressure load controlled by the wall plate is 72.3kpa (including water flow force), and the maximum spacing between the vertical ribs is 300mm. It can be obtained by taking a single wide wall plate for calculation \( \sigma_{\text{max}} = 137 \text{MPa} < [\sigma] = 170 \text{MPa} \). The maximum spacing of ring plate is 1.2m, and single vertical rib bears the maximum load: \( q = 72.3 \times 0.3 = 21.7 \text{KN/m} \). Considering the common stress of the wall panel, the stress of the vertical rib can be calculated \( \sigma_{\text{max}} = 150 \text{MPa} < [\sigma] = 170 \text{MPa} \). Therefore, both the wall panel and the vertical rib meet the specification requirements.
It can be seen from Figure 2 that the maximum combined stress of 12 × 220 + 14 × 150 mm ring plate is 23 MPa, and the maximum combined stress of 12 × 200 mm ring plate is 40 MPa, both of which are less than 170 MPa, meeting the specification requirements. The maximum axial pressure of ∠75 × 6 is 54kN. According to the code for design of steel structures, the reduction coefficient of single angle steel connected on one side under axial compression is 0.6 + 0.0015 λ. In this model, λ = 1700 / 23 = 74, i.e. the reduction coefficient is 0.78, the stability coefficient is 0.726, and the maximum axial force of angle steel is 54kn < 0.78 × 170 × 879.7 × 0.726 / 1000 = 84.6kN, which meets the specification requirements. The maximum axial pressure of ∠100 × 10 is 57kN. Similarly, 57 < 0.69 × 170 × 1926 × 0.823/1000 = 185kN can be obtained by calculation, which meets the requirements of the specification. As can be seen from Figure 2f, the maximum effective stress value of the bulkhead is 16MPa, which is less than 170MPa, meeting the specification requirements.

2) Case 2: Cofferdam pumping condition

After the mud is sucked and sunk to the design elevation in the cofferdam, the bottom sealing concrete shall be constructed. After the bottom sealing concrete reaches the design strength, 3m concrete shall be poured into the cofferdam wall plate. The total height of water in the wall plate shall be 4.5m due to the pumping in the cofferdam wall plate. The water in the cofferdam shall be pumped to the top of the bottom sealing concrete, and the cushion cap shall be constructed. At this time, the cofferdam bears the water pressure load and earth pressure load caused by the difference between the water head inside and outside the cofferdam, as shown in Figure 3. In this case, the stress of the side plate above the filled concrete is mainly calculated. Calculated by equation (1). Midas 2006 is also used to establish the overall model, and the joints of cofferdams below 0.5m from the top of the bottom sealing concrete are hinged. Other settings are the same as Case 1, and the calculation results are shown in Table 3.

![Figure 3. Cofferdam pumping load (mm)](image)

| Specifications          | Stress (MPa) | Allowable stress (MPa) | remarks                                      |
|-------------------------|-------------|------------------------|----------------------------------------------|
| Δ=12, b=200mm           | 107         | 170                    | Upper and lower horizontal ring plate        |
| Δ=12, b=220mm+Δ=14,b=150mm | 98          | 170                    | Middle horizontal annular plate              |
| ∠75×6                   | -41kN       | 84.6kN                 | Horizontal angle steel                       |
| ∠100×10                 | -164kN      | 185kN                  | Horizontal angle steel                       |
| Δ=14                    | 125         | 170                    | panel separating one cabin from another      |
It can be seen from table 3 that the maximum combined stress of $12 \times 220 + 14 \times 150$ mm ring plate is 98MPa, the maximum combined stress of $12 \times 200$ mm ring plate is 107MPA, the maximum axial pressure of $\angle 75 \times 6$ is 41KN, the maximum axial pressure of $\angle 100 \times 10$ is 164kn, and the maximum effective stress of compartment plate is 125mpa, all of which can meet the specification requirements.

3) Case 3: Working condition of bottom inner support removal

When the concrete strength of the lower bearing platform meets the requirements, the inner support crossbar shall be removed, and the cofferdam wall plate shall be supported by the lower bearing platform, and the pier column shall be constructed. The cofferdam mainly bears the internal water of the wall plate and the external water pressure of the cofferdam. Under this working condition, the stress of the side plate above the filled concrete is mainly calculated. According to the structural design of the cofferdam, the gap between the inner side of the cofferdam and the edge of the bearing platform is 500mm. The gap is filled with concrete, and its height is flush with the top of the bearing platform. Similarly, equation (1) is used to calculate the flow force. In the finite element model, the concrete in the cofferdam wall plate is built by solid element, and the other conditions are the same as those in Case 2. The calculation results are shown in Table 4.

![Figure 4. Working condition load of bottom inner support removal (mm)](image)

**Table 4. Calculation results of bottom internal support removal condition**

| Specifications | Stress (MPa) | Allowable stress (MPa) | remarks |
|----------------|-------------|------------------------|---------|
| $\Delta=12, b=200$mm | 58 | 170 | Upper and lower horizontal ring plate |
| $\Delta=12$, $b=240$mm+$\Delta=14, b=150$mm | 120 | 170 | Middle horizontal annular plate |
| $\angle 75\times 6$ | -75kN | 84.6kN | Horizontal angle steel |
| $\angle 100\times 10$ | -168kN | 185kN | Horizontal angle steel |
| $\Delta=10$ | 153 | 170 | panel separating one cabin from another |
It can be seen from table 4 that the maximum combined stress of $12 \times 220 + 14 \times 150$ mm ring plate is 120 MPa, the maximum combined stress of $12 \times 200$ mm ring plate is 58 MPa, the maximum axial pressure of $\angle 75 \times 6$ is 75 kn, the maximum axial pressure of $\angle 100 \times 10$ is 168 kn, and the maximum effective stress of compartment plate is 153 MPa, all of which can meet the specification requirements.

4) Case 4: Calculation of back cover concrete

According to the calculation of pumping water level + 180.3 m, the thickness of the bottom seal is calculated as 2.3 m. The bottom elevation of the bottom seal concrete is + 166.89 m, which bears the buoyancy caused by the water head difference of 13.41 m. The numerical model of the bottom seal concrete and the pile is established, and the pile length is chosen to be 5 m. Considering the influence of cofferdam self-weight and bottom sealing concrete self-weight, the allowable cohesive force is 15.0 t/m², and the thickness of bottom sealing concrete shall not be less than 2.3 m during cofferdam construction. When the water level is high, the calculation model is shown in Figure 5 (a), and the main tensile stress of the bottom sealing concrete is shown in Figure 5 (b). It can be seen from the figure that the maximum main tensile stress of the bottom sealing concrete is 0.72 MPa, which meets the stress requirements. According to the calculation, the cohesive force of the pile casing is 12.4 t/m², which is less than the allowable value of cohesive force and meets the design requirements.

The calculation model at low water level is shown in Figure 6 (a), and the main tensile stress of the bottom sealing concrete is shown in Figure 6 (b). It can be seen from the figure that the maximum main tensile stress of the bottom sealing concrete is 0.82 MPa, which meets the stress requirements. According to the calculation, the cohesive force of the pile casing is 13.8 t/m², which is less than the value of the allowable cohesive force and meets the design requirements.

5. Construction Plan

The construction of double-wall steel cofferdam has two processes: "pile before weir" and "weir before pile". After comparison and selection, the construction period of "weir before pile" is long and the
construction is difficult. At the same time, large floating ship is required to hoist the steel cofferdam, so the site is limited and it is not easy to control the sinking deviation of the cofferdam. The scheme of "pile before weir" can process the steel cofferdam at the same time of pile foundation construction to save the construction progress. Meanwhile, the drilling platform can be used as the assembly and sinking platform of the steel cofferdam, which can greatly improve the working environment of steel cofferdam installation and sinking. The steel casing is used to set the positioning device to avoid the deviation and improve the positioning accuracy when the steel cofferdam sinks. Therefore, the scheme of "pile before weir" is adopted for the construction of pier cap in water. First, according to the design drawing of steel cofferdam, the semi-finished cofferdam shall be fabricated in the cofferdam processing yard. When the pile foundation is completed, the steel cofferdam shall be assembled on the drilling platform, and then the four pile steel casings shall be connected. The steel cofferdam shall be placed in place section by section.

The construction process of double-wall steel cofferdam is as follows: a) setting up of drilling platform, b) pile foundation construction and processing of off-site steel cofferdam in sections at the same time, c) removing the drilling rig and removing the platform within the bearing platform range, d) transporting the processed sections outside the site to the platform, e) lifting frame and guide frame installation, f) assembling, lowering the first section of cofferdam on the platform, water injection sinking, g) the second and third sections are connected with height, h) mud suction, concrete pouring and filling, i) steel cofferdam positioning bed, j) bottom sealing concrete pouring, k) lifting frame, l) guide frame removal, m) internal support construction, n) construction platform, o) pier body construction, p) cofferdam removal.

6. Conclusion
The application of double-wall steel cofferdam is more and more in the construction of bridge deep-water foundation. Although steel cofferdam is a temporary structure, it plays an important role in the construction of bridge deep-water foundation. In the second Songhuajiang super large bridge, the double-wall steel boxed cofferdam with deep water bearing platform adopts the scheme of pile first and weir second. Through the numerical simulation of Midas 2006, the stress of each component under the most unfavorable working condition in the whole process of structural construction is simulated, which guarantees the structural safety, reliability and economic rationality of the cofferdam design. The construction of cofferdam adopts the scheme of lifting and sinking steel cofferdam with a lifting system, which can effectively improve the construction progress and provide basis and reference for the construction of deep-water foundation in large-scale bridge engineering in the future.

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