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Analysis of Large Double-Wall Steel Cofferdam Design and the Piling Before Cofferdam Construction Methodology

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Abstract. Double-wall steel cofferdam has become an ideal enclosure structure in deep-water foundation construction due to its virtue of high strength, high rigidity and good waterproof performance, and has been applied in bridge construction on a large scale. This paper takes the construction of Pier 5 bearing platform of Leishui Large-Span Bridge with water depth of 18m as the engineering background, and introduces the design of double-wall steel cofferdam for deep-water bearing platform and the design parameters of double-wall steel cofferdam with height of 20.8m. The paper adopts Midas/Civil to establish finite element model for the cofferdam structure, to check the strength, stiffness and stability of the cofferdam structure. The paper gives a detailed introduction to the checking of the cofferdam's anti-floating, anti-slumping, and key weld joints, etc. In addition, for the methodology of piling before cofferdam construction, the paper introduces the design and technology of the first section assembly platform and lifting system of the cofferdam.

Keywords. Deep water, double-wall steel cofferdam, piling before cofferdam construction, assembly platform, lifting system, Midas

1. Introduction

Double-wall steel cofferdam has become an ideal enclosure structure in deep-water foundation construction due to its virtue of high strength, high rigidity and good waterproof performance, and has been applied in bridge construction on a large scale. Double-wall steel cofferdam is a construction auxiliary measure, and there is no specific design scheme about it in the design of general bridge construction. Double-wall steel cofferdam is generally designed by construction unit, so its design has a strong relationship with the experience of the construction unit. The form of double-wall steel cofferdam can be designed according to the shape of bearing platform, burial depth, etc. For example: Xijiang Large-Span Bridge [1] adopts rectangular structure, BaoLan Line Weihe Bridge No.14 Pier 6, 7 [2] adopts circular structure, Yingwuzhou Yangtze River Bridge Tower No.2 [3] adopts "rectangle + short-side semi-circular" structure, Wufengshan Bridge main bridge bearing platform [4] adopts dumbbell-type structure. The design of double-wall steel cofferdams by the construction unit is overall conservative and economically inefficient, and it is also often inconvenient for the

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construction of the project because of incomplete considerations. This paper introduces the design of 20.8m rectangular double-wall steel cofferdam and the technology of piling before cofferdam construction, with the background of the construction of Pier 5 bearing platform of Leishui Large-Span Bridge.

2. Project Overview

The main bridge of Leishui Large-Span Bridge adopts a 70m+130m+70m continuous rigid frame structure, with the transitional Pier 4 and main Pier 5 and 6 located in the water. Among them, Pier 5 has the deepest water depth, reaching 18 meters during a once-in-a-decade flood. The cap of Leishui Large-Span Bridge is placed on the riverbed, requiring the use of double-wall steel cofferdams for cap construction. The cap is divided into left and right spans with a clear distance of 4 m, and its dimensions are 9.5m (transverse bridge direction) × 15m (longitudinal bridge direction) × 4.5m (height). Water transportation and floating crane construction are not suitable for the construction site, and a steel cofferdam processing yard can be set up on the shore. Therefore, the methodology of piling before cofferdam construction [5-6] is adopted. To ensure smooth transportation of construction materials, a long plank bridge is constructed along the route direction at the bridge site to cross and open a longitudinal access road. A “loop” shaped support plank bridge is designed at the pier to facilitate the transportation and installation of steel cofferdam sections, as shown in figure 1.

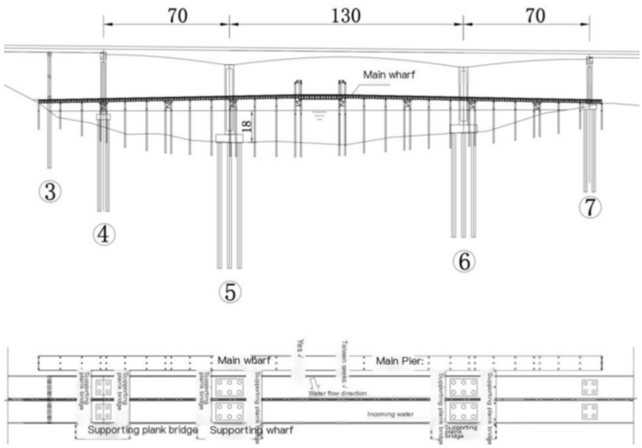


Figure 1. Layout of the main bridge type of Leishui Large-Span Bridge

3. Design and Calculation of Double-Wall Steel Cofferdam

3.1. Design Plan for Double-Wall Steel Cofferdam

The specific parameters of the design plan for the double-wall steel cofferdam for Pier 5 of the LeiShui Large-Span Bridge are shown in table 1, and the layout of the double-wall steel cofferdam is illustrated in figure 2. The design primarily considers the following aspects:

(1) Plane dimensions

A single integrated cofferdam is set for the left and right bearing platforms. The front and rear sides consider using the inner wall of the cofferdam as a template, while the left and right sides account for pier construction space and bearing platform template installation, with a clear distance of 1m between the inner wall of the cofferdam and the side of the bearing platform.

(2) Height

The bottom of the bearing platform, excluding a 20cm cushion layer, serves as the top surface of the bottom-sealing concrete. The thickness of the bottom-sealing concrete is determined through calculations, which then establish the elevation of the cofferdam bottom. Since the water level varies minimally around the normal water level +73.00, the elevation of the top surface is set at the once-in-a-decade flood level +75.50 to ensure that the construction process is largely unaffected by floods.

(3) Layered design

In the vertical direction, a layered design is adopted based on different stress levels, with adjustments to component parameters in each layer according to the stress conditions.

(4) Plane block design

According to the plan dimensions, each layer is divided into 16 standard blocks and 4 corner blocks on the plan. This simple block division facilitates material procurement and processing, while also considering the maximum weight for segmental lifting and installation.

(5) Internal support setup

Referencing the optimization design of steel cofferdam support systems by Qin Dayan and Luo Xiaobin [7], internal supports are optimized with a total of three layers positioned at distances of 3m, 7.5m, and 10.5m from the top. Concrete placement within the compartments extends above the elevation of the bearing platform, avoiding the inconvenience of internal support installation within the bearing platform elevation during construction.

Table 1. Design parameters of steel cofferdam for Pier 5 of Leishui Large-Span Bridge.

Number	Structure name	First floor (4.5m)	Second layer (4.3m)	Third layer (6m)	Fourth layer (6m)
1	Platform size (m)	9.5 × 15 × 4.5			
2	Plane size of cofferdam (m)	27.812 × 18.212			
3	Cofferdam height (m)	20.8			
4	Vertical segmentation	4.5	4.3	6	6
5	Horizontal partitioning	20			
6	Maximum weight of blocks (t)	7.5	6.0	12.4	9.3
7	Double-wall thickness (mm)	1412			
8	Internal support spacing (m)	3 lanes, 3m, 7.5m, 10.5m from the top			
9	Internal support material (mm)	630 × 10			
10	Wale	2I56a			
11	Double-wall steel plate thickness(mm)	6	6	8	6
12	Ring plate size (mm)	250 × 12	250 × 12	300 × 16	250 × 16
13	Layered spacing of ring plate (m)	1	1	0.75	1
14	Thickness of compartment	12	12	20	16

	plate (mm)				
15	Spacing between compartments (m)	Standard 4.0			
16	Horizontal truss (mm)	L80 × 8	L80 × 8	L100 × 10	L80 × 8
17	Vertical stiffener (mm)	L75 x 50 x 6 @ 300			
18	Thickness of bottom sealing concrete (m)	3.2mC30			
19	Concrete height inside the compartment (m)	9.0mC30			
20	Steel cofferdam weight (t)	635.1			

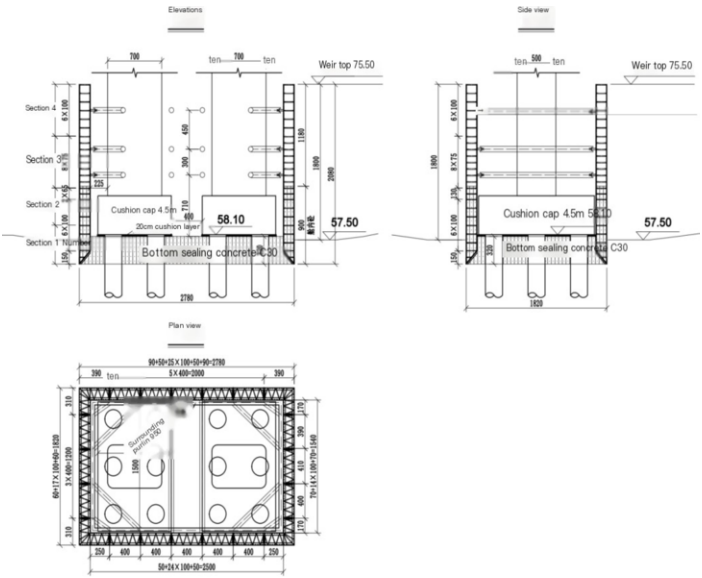


Figure 2. Layout of steel cofferdam.

3.2. Structural Verification of Double-Wall Steel Cofferdam

(1) Model Establishment and Boundary Conditions

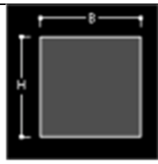
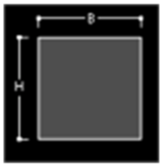
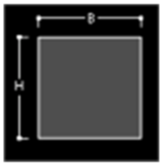
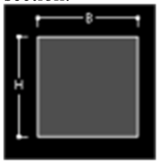
The analysis and calculation are conducted by Midas/Civil software. For the calculation of the steel cofferdam of Pier 5, the cutting edge with a height of 1.5m is not considered. The modeling parameters for this model are as follows:

1) Material Parameters, Section Parameters, and Element Types

The steel cofferdam is modeled and analyzed by Midas/Civil. Beam elements are used to simulate various members such as annular plates, horizontal trusses, wales, and internal supports. Bulkhead plates are simulated by plate elements, double-wall panels are simulated by stiffened rib plates, and the bottom-sealed concrete and concrete within the bulkheads are simulated by solid elements. The main element types, material names, and section shape dimensions are shown in table 2.

Table 2. Statistics of cross sections of main members.

Member Name	part	material	section	Section size/mm	Unit type	Remarks
Annular plate	First and second floors	Q235	Solid abdominal rectangle	H * B=250 * 12	Beam element	Solid abdominal rectangle:

	(4.5+4.3m)					 Box section:  Angle steel section:  Circular cross-section: 
	Third layer (6m)	Q235	Solid abdominal rectangle	H * B=300 * 16	Beam element	
	Fourth layer (6m)	Q235	Solid abdominal rectangle	H * B=250 * 16	Beam element	
Horizontal truss (wall support)	First and second floors (4.5+4.3m)	Q235	Angle steel	H * B * tw * tf= 80 * 80 * 8 * 8	Beam element	
	Third layer (6m)	Q235	Angle steel	H * B * tw * tf= 100 * 100 * 10 * 10	Beam element	
	Fourth layer (6m)	Q235	Angle steel	H * B * tw * tf= 80 * 80 * 8 * 8	Beam element	
Wale	/	Q235	Box type	D * B * tw * tf=560 * 300 * 12.5 * 21	Beam element	
Internal support	/	Q235	rotundity	D * tw=630 * 10	Beam element	
Compartmentalized version	First and second floors (4.5+4.3m)	Q235	Plate thickness	tw=12	Board unit	
	Third layer (6m)	Q235	Plate thickness	tw=20	Board unit	
	Fourth layer (6m)	Q235	Plate thickness	tw=16	Board unit	
Double-wall panel	The first, second, and fourth floors	Q235	Stiffening rib plate	Plate thickness tw=6, stiffener L75 x 50 x 6 @ 300	Board unit	
	Third layer	Q235	Stiffening rib plate	Plate thickness tw=8, stiffener L75 x 50 x 6 @ 300	Board unit	
Bottom sealing concrete	/	C30	entity	/	Physical unit	
Concrete inside the compartment	/	C30	entity	/	Physical unit	

2) Boundary Conditions

The bottom-sealed concrete of the steel cofferdam is securely connected to the riverbed and the completed pile foundation, preventing any movement or rotation. The steel cofferdam, bottom-sealed concrete, and concrete within the bulkheads are all consolidated with the foundation, constraining freedom in seven directions. The wale and inner annular plate are connected by rigid connections and master-slave constrained connections.

3) Calculation Model

A finite element model of the double-wall steel cofferdam for Pier 5 is established based on the design plan. The finite element model is shown in figure 3.

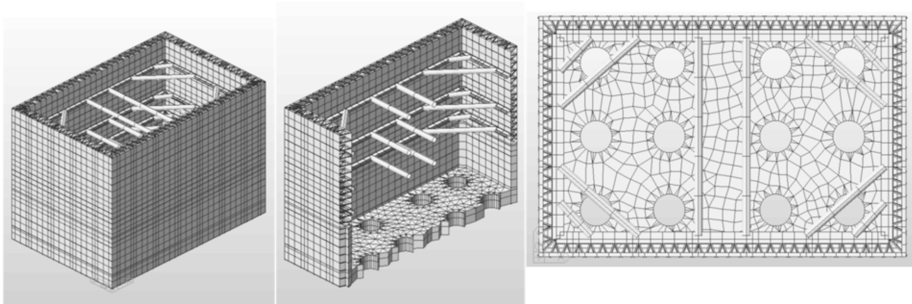


Figure 3. Calculation model of double-wall steel cofferdam.

(2) Load Calculation and Working Condition Analysis

The construction process of the double-wall steel cofferdam follows the sequence of "cofferdam assembly and lowering (with internal support installed simultaneously) → bottom-sealing concrete construction → water pumping within the cofferdam". Under the combined effects of structural gravity, hydrostatic load, hydrodynamic load, and earth pressure, the most unfavorable working condition for the double-wall steel cofferdam occurs when the water level rises to the top elevation of the cofferdam and water is pumped within the cofferdam to the top surface of the bottom-sealed concrete. Loads are considered based on this most unfavorable condition.

1) Structural Self-Weight

The structural self-weight is automatically calculated by the Midas model.

2) Hydrostatic Load

The hydrostatic load adopts a fluid pressure load, with a reference height of 19.3m and a uniformly distributed pressure load P_0=0kN/m^2. The fluid unit weight is g=9.8kN/m³. The hydrostatic pressure at a depth of 19.3m is calculated as 9.3m × 9.8kN/m³ = 189.14kN/m^2. The schematic diagram of hydrostatic load is shown in figure 4.

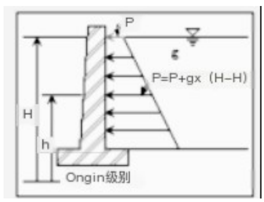


Figure 4. Schematic diagram of fluid pressure load loading.

3) Hydrodynamic Load

The hydrodynamic load is distributed on the upstream face of the cofferdam, with the pressure forming an inverted triangular distribution. The hydrodynamic pressure at the riverbed bottom is 0, and it is maximum at the water surface. The maximum hydrodynamic pressure is calculated as:

$$Q_{max} = k\frac{\gamma v^2}{g}\text{=1.3×9.8×1.52/9.8=2.92kN/ m}^2$$

where K is the shape coefficient of the upstream face. For a rectangular shape with the long side parallel to the flow, K is taken as 1.3.

4) Earth Pressure Load

Since the bottom-sealed concrete is higher than the riverbed outside the cofferdam, the influence of earth pressure is not considered.

(3) Analysis Results

1) Verification of Strength, Stiffness, and Stability of the Cofferdam Structure

The calculations are performed using the allowable stress method according to the "Code for Design of Steel and Timber Structures of Highway Bridges and Culverts" [8]. For Q235 steel, the allowable stress for bending and combined stress [σ] is 145MPa, and the allowable shear stress [τ] is 85MPa. The results are summarized in table 3 and all meet the requirements.

Table 3. Cofferdam verification results.

Number	project	Calculation results	Allowable value	Whether it meets the requirements
1	Combined stress of ring plate (MPa)	115.6	145	satisfy
2	Combined stress of truss (MPa)	101.6	145	satisfy
3	Combined stress of purlin (MPa)	503	145	satisfy
4	Internal support combination stress (MPa)	86	145	satisfy
5	Panel combined stress (MPa)	91.2	145	satisfy
6	Combined stress of partition board (MPa)	91.2	145	satisfy
7	Shear stress of ring plates, horizontal trusses, wales, and internal supports	20.1	85	satisfy
8	Shear stress of panel and partition board (MPa)	49.0	85	satisfy
9	Displacement deformation (mm)	4.3	10	satisfy
10	Minimum eigenvalue	4.5	4	satisfy

2) Anti-Floating Verification of Cofferdam

After the completion of the bottom sealing of the double-wall steel cofferdam, researchers conduct an anti-floating verification during the pumping process within the cofferdam. The bottom-sealed concrete of the double-wall steel cofferdam is graded as C30 with a thickness of 3.2m. At the most unfavorable construction water level, when the water inside the cofferdam is completely pumped out, the head pressure height is the difference between the highest water level and the bottom surface of the sealed concrete, which is 75.5 - 54.7 = 20.8m.

The anti-floating verification formula for the double-wall steel cofferdam is: F (the buoyancy of the double-wall steel cofferdam after pumping) < G (the self-weight of the double-wall steel cofferdam + the weight of the concrete filled between the double walls + the weight of the water between the double walls + the weight of the sealed concrete + the frictional resistance between the sealed concrete and the steel casing), with a certain margin coefficient ensured. According to the specification [9], the anti-floating coefficient should be 1.15. Currently, there is no normative value for the bond stress between the steel casing and concrete. Sun Yingxue et al. suggested in their research "Study on the Interaction between the Bottom-Sealed Concrete and Steel Casing of Large Steel Suspension Boxes" that the average ultimate unit frictional resistance of the bottom-sealed concrete should not exceed 370kPa [10]. Yang Hong et al. suggested in their research "Experimental Study and Application of the Grip Force between the Bottom-Sealed Concrete of the Pile Cap and the Steel Casing of the Sutong Bridge" that the grip force coefficient between the pile cap's bottom-sealed concrete and the steel casing should be 370kPa [11]. Considering safety, a value of 150kPa is adopted [7]. Substituting the values into the calculation, the anti-floating coefficient K = G/F = 1.25 > 1.15, which meets the requirements.

3) Anti-Overturning Verification of Cofferdam

When there is no overburden layer and the bottom-sealed concrete has not been constructed, the steel cofferdam has the worst stability against overturning, with the maximum water flow velocity considered as 1.5m/s. The anti-overturning coefficient $K=M_{stability}/M_{inclination}=(G_{self\ weight}+G_{compartment\ concrete} - F_{compartment\ floating}) \times (27.8 \div 2)/(F_{flowing\ water} \times (18-18/3)=31.9>1.5$. Therefore the steel cofferdam meets the safety requirements for anti-overturning.

4) Verification of Horizontal Truss Welds

The design of the connection between the horizontal annular plate and the angle steel is based on the weld connection calculation in the "Road and Bridge Construction Calculation Manual" P420. The horizontal annular plate and the angle steel are welded on three sides (see figure 5), but the calculation is based on welding on two sides: for the back of the equal-leg angle steel, K1 = 0.7; for the tip of the leg, K2 = 0.3.

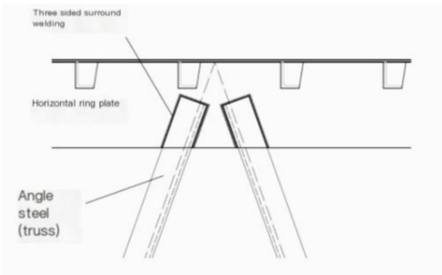


Figure 5. Schematic diagram of horizontal truss welds.

① L100 × 10 verification calculation

The maximum axial force is 121.9KN, and the allowable stress of the weld seam is 85MPa. The size of the leg for leg back welding is ht=10mm, the size of the leg for leg tip welding is ht=8mm, and the length of the weld seam is L=180mm.

Stress of leg back weld seam $\tau_1=K1N/(0.7ht\ \Sigma L) =67.7MPa<[\tau]= 85MPa$, meets the requirements.

Stress of limb tip weld seam $\tau_2=K2N/(0.7ht\ \Sigma L) =36.3MPa<[\tau]= 85MPa$, meets the requirements.

Therefore, the L100 × 10 weld seam of the horizontal truss meets the requirements.

② L80 × 8 verification calculation

The maximum axial force is 88KN, and the allowable stress of the weld seam is 85MPa. The size of the leg welding at the back of the limb is ht=8mm, the size of the leg welding at the tip is ht=6mm, and the length of the weld seam is L=130mm.

Stress of leg back weld seam $\tau_1=K1N/(0.7ht\ \Sigma L) =84.6MPa<[\tau]= 85MPa$, meets the requirements.

Stress of limb tip weld seam $\tau_2=K2N/(0.7ht\ \Sigma L) =48.4MPa<[\tau]= 85MPa$, meets the requirements.

Therefore, the L80 × 8 weld seam of the horizontal truss meets the requirements.

(4) Calculation Conclusion

The analysis of stress, displacement, structural stability, anti-floating calculation, anti-overturning calculation, and horizontal truss weld calculation under the most unfavorable working conditions of the double-walled steel cofferdam structure of Pier 5 of the LeiShui Large-Span Bridge shows that the overall safety of the double-wall steel cofferdam structure is ensured.

4. The Piling before Cofferdam Construction Methodology

4.1. Assembly Platform for the First Section of the Cofferdam

During construction, brackets are installed on the steel pile casings, and then support beams are arranged on the brackets to form an assembly platform. The first section of the cofferdam is assembled on this platform. The brackets of the assembly platform adopt double-spliced I25a, the support beams adopt double-spliced 45a, and the support frame adopts double-spliced [10]. The design of the assembly platform is shown in figure 6, and the on-site assembly of the first section of the steel cofferdam is shown in figure 7.

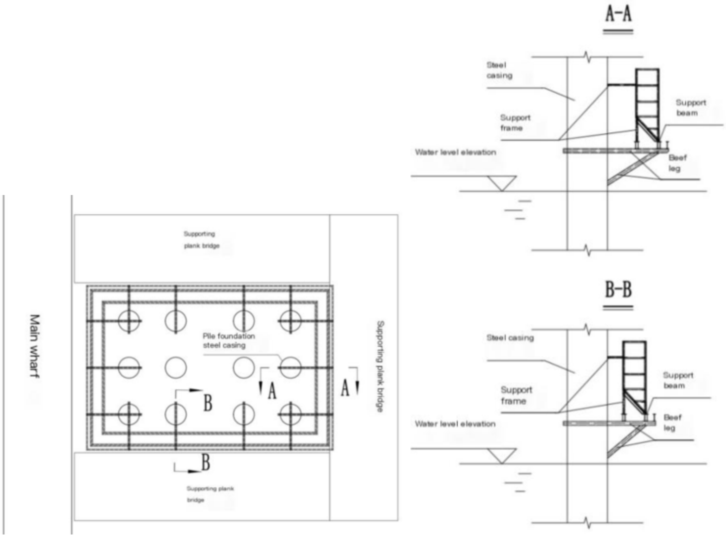


Figure 6. Layout of assembly platform.

Figure 7. Assembly of the first section of steel cofferdam.

4.2. Lifting System for the First Section of the Cofferdam

The steel cofferdam lifting system (figure 8) is equipped with support steel pipes with a diameter of 630 mm and a wall thickness of 10 mm at the top of the steel pile casing and on the trestle platform. Double-splice 56 steel is installed above the support steel pipes as the main load-bearing beam for lifting and lowering. The lifting system is designed with six lifting points on the upper part of the main load-bearing beam, each equipped with one set of lifting devices. Each set consists of a 50t hydraulic jack and two φ32 finished rolling deformed steel bars. The lifting system is counter-pulled through the top beam, lifted first, and then the assembly platform is removed before lowering the first section of the cofferdam to float on the water surface. This lifting system ingeniously utilizes two bolts on the jack and the distribution beam, making the operation relatively simple. The process of lifting and lowering the cofferdam is stable with good synchronization, less prone to tilting, and ensures safety during the sinking process. The scene of lifting and lowering the first section of the cofferdam into the water is shown in figure 9.

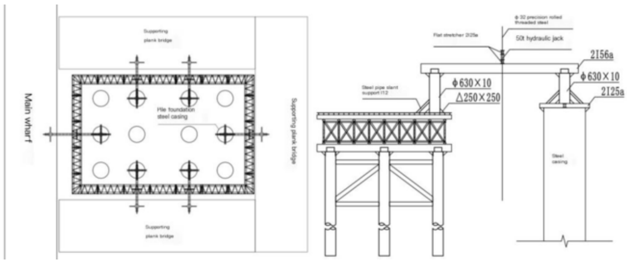


Figure 8. Layout of steel cofferdam lifting points.

Figure 9. The first section of the cofferdam is suspended and placed into the water.

4.3. Extension and Sinking of the Cofferdam

The extension and assembly of the cofferdam commence simultaneously from two diagonally opposite corners towards the other two directions, with closure at the remaining two diagonally opposite corners. During the extension process, limit blocks are welded onto the top of the double-wall steel cofferdam of the bottom section to ensure accurate positioning of each steel cofferdam block. Throughout the extension process, all wales and internal supports are constructed simultaneously. Upon completion of the closure of each section, it is flooded and sunk to the designated elevation to facilitate the extension of the next section. To ensure reliable stress distribution on the cutting edge at the bottom, after the second section is lowered into position (before touching the riverbed), concrete is placed in the cutting edge area, with a placement height 20cm above the elevation of the cutting edge top. The cofferdam heightening is shown in figure 10.

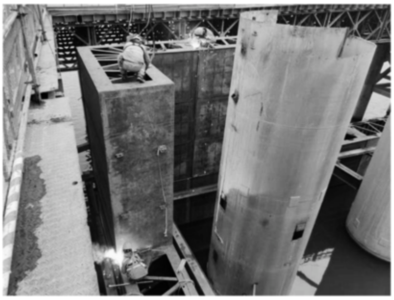


Figure 10. Cofferdam heightening.

4.4. Construction of Bottom Sealing Concrete

The construction of bottom sealing concrete is carried out after the cofferdam is fully lowered and stably positioned. The bottom sealing concrete is C30 underwater concrete, applied using a multi-point grouting method. Considering a single pipe with an effective radius of 5m, a total of 12 grouting points are arranged. The coverage of all tremie pipes encompasses the entire concrete placement area, as shown in figure 11. The construction of bottom concrete pouring is shown in figure 12. Prior to placing the bottom sealing concrete, the following preparations must be made: ①Control the elevation of the riverbed before placement, clear protruding rock pinnacles to ensure a suitable thickness of the bottom sealing concrete; ② Clean the sediment beneath the cutting edge to prevent the formation of a sediment layer between the bottom sealing concrete and the steel cofferdam, which could lead to water leakage; ③ Clean the outer side of the steel casing of the pile foundation to ensure proper stress distribution between the bottom sealing concrete and the steel casing; ④ Seal the cutting edge on the outer side of the cofferdam to prevent the concrete from contacting the flowing water, which could cause washing of the concrete.

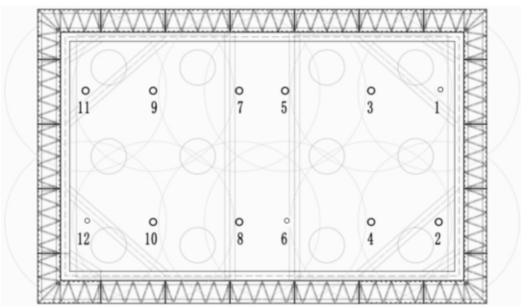


Figure 11. Schematic diagram of layout points and impact range for pouring bottom concrete.

Figure 12. Construction of bottom concrete pouring.

5. Conclusion

On July 25, 2023, the dewatering of the steel cofferdam for Pier 5 of the Leishui Large-Span Bridge was successfully completed. Post-dewatering, the cofferdam exhibited excellent water isolation with no leakage, maintaining a stable and secure structure. This ensured a spacious working area for the construction of the pile cap and subsequent substructure in deep water areas. The innovative layered and internal support design of the steel cofferdam has provided valuable insights for similar projects.

a) The layered design of the steel cofferdam significantly reduces the amount of steel used, aligning better with the stress characteristics of the cofferdam. This approach also allows for a reduction in the height of each layer, achieving a more economical use of materials.
b) The internal support design for the steel cofferdam of Pier 5 of the Leishui Large-Span Bridge takes full advantage of its structural characteristics. Symmetrically arranged support points improve the overall stress distribution of the cofferdam and facilitate the construction of subsequent pier columns. Additionally, by controlling the pouring height of concrete within compartments, the strength and rigidity of the cofferdam's bottom box are enhanced. This reduces the number of internal supports and wales at the base of the cofferdam, minimizing the impact on the pile cap construction.
c) The structural verification of the steel cofferdam for Pier 5 includes checks for strength, rigidity, and stability. It also assesses the cofferdam's resistance to buoyancy, overturning, and the integrity of major load-bearing welds, ensuring the safety of the bridge. Furthermore, the innovative design of the initial assembly platform and lifting system for this project has ensured the smooth construction of the steel cofferdam.

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