Design and Construction of the Interlocking Steel Pipe Pile Cofferdam for the Main Pier of the Shuidu Second Bridge located in Danjiangkou City

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Abstract. The main bridge of the Danjiangkou Shuidu Second Bridge is a three-span continuous steel box girder arch bridge with a total length of (227.5+225+227.5) meters. The 20th pier of the bridge is located in the main channel of the Han River. During the construction period, the designed water depth is approximately 9.5 m, requiring the installation of steel cofferdams for underwater construction. Considering the design conditions, a comparative analysis was conducted, and the decision was made to use interlocking steel pipe piles for the cofferdam. The cofferdam is arranged in a rectangular shape with a plan dimension of 44.06 m × 18.52 m and a height of 21 m. It employs Φ820×14 steel pipe piles, with 4 layers of internal support and a 3 m thick C30 underwater concrete base. Through analysis and calculations under different working conditions, the results indicate that the cofferdam structure is safe and reliable. The construction's critical techniques for the interlocking steel pipe pile cofferdam are detailed in the description.

Keywords: lock buckle steel pipe pile; cofferdam; underwater construction; water sealing.

1 Introduction

Cofferdams refer to temporary retaining structures used in bridge or hydraulic engineering for pile foundation or pier construction in water. The main function of a cofferdam is to prevent water and sand, block other debris from scouring, etc. When the cofferdam is closed, the accumulated water inside the cofferdam is extracted, after that, the soil layer is replaced and the foundation pit is excavated, and finally the foundation is laid. At present, there are several common types of waterproof cofferdams in engineering, including earth rock cofferdams, steel sheet pile cofferdams, double wall steel cofferdams, and lock buckle steel pipe pile cofferdams.

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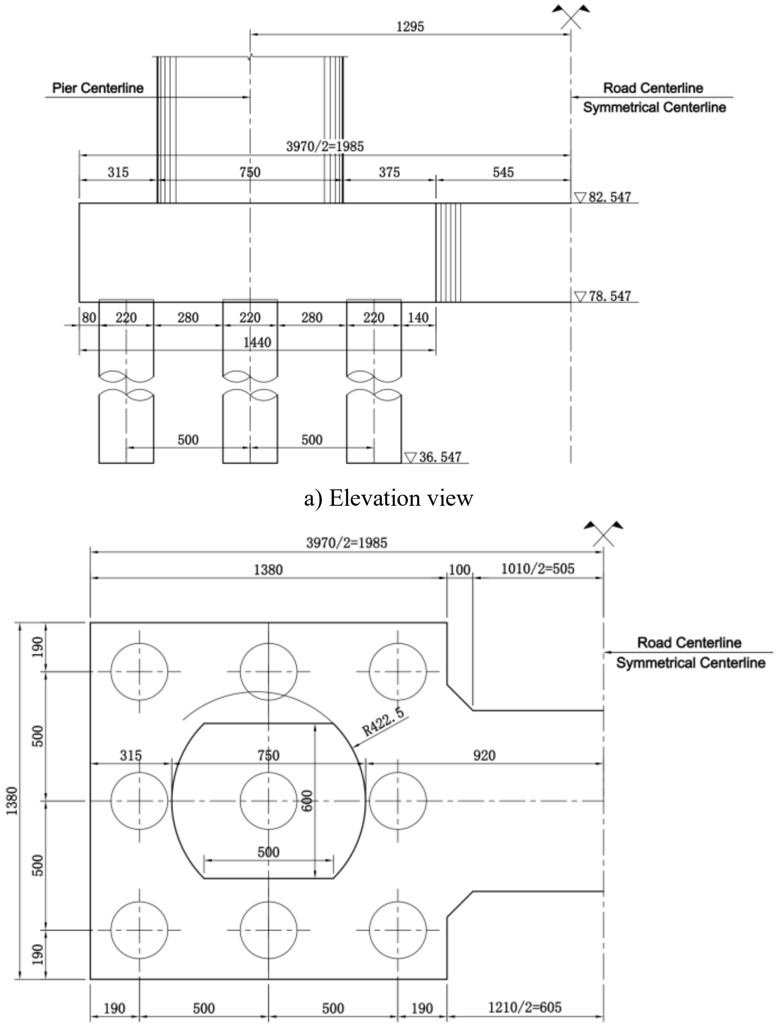
Foreign engineers early summarized the engineering application of steel pipe piles and began to study new forms of connection for steel pipe piles, proposing the type of locking steel pipe piles [1]. Until the late 20th century, due to the advantages of high compressive strength, good ductility, and reliable bearing capacity of steel pipe piles, some scholars began to study the use of new lock buckle forms to connect steel pipe pile cofferdams as a whole. This type of cofferdam structure has been widely used in various engineering projects due to its strong flexibility, fast construction, and good economy [2-4].

Lock buckle steel pipe pile cofferdam is a type of cofferdam that drives a single steel pipe pile into the bearing layer in water, and then connects each steel pipe pile into a whole through the lock buckle. Its mechanism is to balance the combined effect of external soil pressure, water pressure, and other loads through the stiffness provided by the steel pipe pile itself and the support inside the cofferdam. The main advantages of locking steel pipe pile cofferdam include structural stability, high strength and stiffness, strong environmental adaptability, and flexible parameters selection. Due to the above advantages, this type of cofferdam has good penetration and can adapt well to complex geological and hydrological conditions. It also has considerable raw material recovery rate and high work efficiency.

This article is based on the lock buckle steel pipe pile cofferdam project of Danjiangkou Shuidu Second Bridge, and studies the feasibility and rationality of implementing lock buckle steel pipe piles on sandy gravel riverbed under deep water conditions. At present, there are few engineering examples of the application of lock buckle steel pipe pile cofferdam on gravel riverbed in China. Therefore, conducting detailed theoretical analysis and practical exploration on it can provide reference for future similar engineering design and construction

2 Project Overview

The Shuidu Second Bridge is a crucial cross-river transportation located in Danjiangkou City, spanning the Han River. The main bridge is designed as a three-span continuous steel box girder arch bridge with a total length of (227.5+225+227.5) meters. The 20th pier of the main bridge is situated in the main channel of the Han River, using twin solid piers. The pier's pier cap adopts a dumbbell-shaped structure, with a outline size of 39.7 m×13.8 m, a thickness of 4 m, and is supported by a foundation consisting of 18 bored cast-in-place piles with a diameter of 2.2 m each. The layout of the foundation structure for the main pier is depicted in Figure 1.



a) Elevation view

b) Planar view

Fig. 1. Layout diagram of the foundation structure for 20th pier (unit: cm)

3 Design conditions

3.1 Hydrology

The bridge site is located 2.1 km downstream of the Danjiangkou Dam, and the navigable opening in the Han River segment is located between the 19th and 20th main piers of the bridge, close to the left bank. The design flood standard for the bridge adopts a 100-year return period, with the corresponding design water level at 94.17 m (1985 national elevation datum, the same below). During the construction period of the bridge, the flood standard is set at a 5-year return period, with a corresponding design water level of 92.36 m.

3.2 Geology

The covering layer at the location of the main piers is the Holocene stratum (Q_4^{1al}) of the Quaternary System, with a thickness of about 6.5 m, consisting of slightly to moderately dense sand, gravel, and pebbles. The underlying bedrock includes muddy sandstone and conglomerate, as well as metamorphic diorite and dioritic greenstone. The lithology of muddy sandstone and conglomerate is soft, belonging to soft or very soft rock. The bearing layer for pile foundation is slightly weathered metamorphic diorite and dioritic greenstone, with a saturated uniaxial compressive strength of 33.3 MPa, at a depth of 36.2 m to 42.0 m.

4 Cofferdam Selection

At the location of 20th pier, the designed water depth is approximately 9.5 m. Considering a foundation embedment of 0.5 m, a pier cap thickness of 4 m, and a 3 m thick underwater concrete base, the cofferdam needs to withstand approximately 17 m of water pressure and 6.5 m of soil pressure. The cofferdam selection, besides meeting basic safety and feasibility criteria, should prioritize simplicity in process, controllable quality, and time-saving measures [5]. Additionally, since the riverbed here is composed of dense gravel and pebbles, regardless of the cofferdam type used, driving or sinking it to the design depth is challenging and positioning is difficult. Therefore, pre-drilling is required before installing or sinking the cofferdam, and the selection should consider the scale and difficulty of pre-drilling [6].

After initial comparisons, it is evident that earth rock cofferdam and sheet pile cofferdams are not suitable. For earth rock cofferdam, it is generally suitable for environments with a water depth of less than 2 meters, unsuitable for the deep-water environment of this project. And for the steel sheet pile cofferdam, Currently, the maximum length of a single sheet pile available on the market is about 18 m, which is insufficient for anchoring directly in this project. Extending the sheet piles poses challenges in terms of driving and water stoppage, with safety concerns also difficult to guarantee [7].

Double-wall steel sheet pile cofferdams exhibit high overall stiffness, good stability, strong impact resistance, and excellent water-stopping performance, especially suitable for deep-water foundations, making them seemingly applicable to this bridge [6].

However, the installation of double-wall steel sheet pile cofferdams requires large lifting equipment and assembly in sections, making the process complex and time-consuming. They cannot penetrate the gravel layer to reach the bedrock by relying on their own weight, necessitating the removal of the entire gravel layer within the cofferdam's plan area through underwater excavation to form a foundation trench. This is followed by drilling along the entire cofferdam's side wall contour in the bedrock layer. The effort involved in milling grooves and drilling is substantial, and once the cofferdam encounters resistance during sinking or if its positioning is off, correction becomes challenging. Furthermore, the dismantling of double-wall steel sheet pile cofferdams is difficult, almost impossible to recover, and incurs high costs [7]. In summary, while the double-wall steel sheet pile cofferdam solution is feasible, it has certain drawbacks.

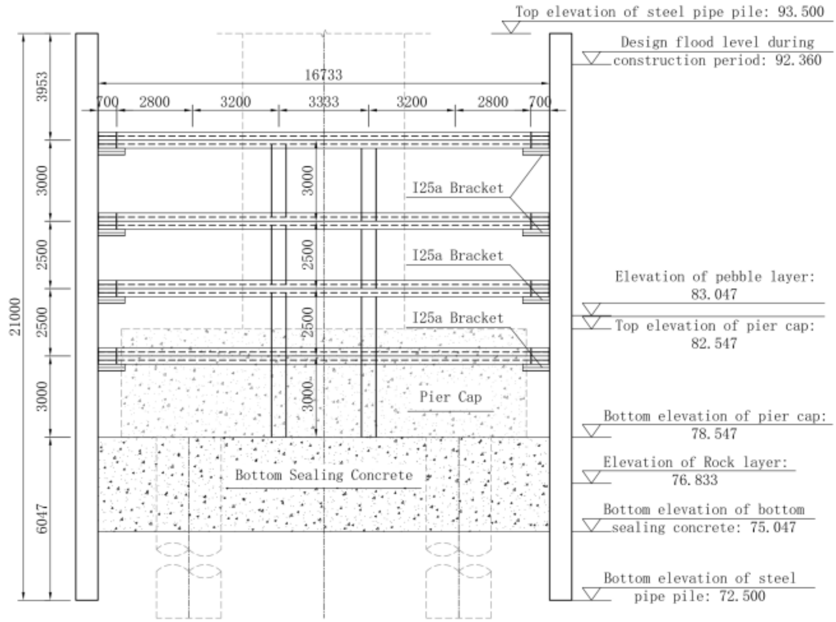
The interlocking steel pipe pile cofferdam has significant stiffness. By setting up an internal support system, its overall stiffness and resistance to lateral forces can meet the requirements of this project. The structure of the interlocking steel pipe pile cofferdam is simple, can be fabricated on-site, and is recyclable, resulting in significant cost savings compared to the double-wall steel sheet pile cofferdam [7]. The construction process of the interlocking steel pipe pile cofferdam is straightforward and, similar to the sheet pile cofferdam, utilizes a crane with a vibrating hammer for installation. This simplifies the process significantly compared to the double-wall steel sheet pile cofferdam, effectively shortening the construction period [8]. The drilling process for interlocking steel pipe piles is uncomplicated. In the process of driving each pile, if resistance is encountered, a drilling rig can be arranged on-site to drill within the pile without the need for pre-drilling. The depth of drilling can also be controlled for each pile according to actual requirements. Overall, considering the assurance of structural safety, the interlocking steel pipe pile cofferdam is a lower-cost, simpler, more time-efficient, and more controllable option than the double-wall steel sheet pile cofferdam. Therefore, after comprehensive evaluation, the interlocking steel pipe pile cofferdam is selected for the underwater foundation construction of 20th pier in this project.

5 Cofferdam Structure Design

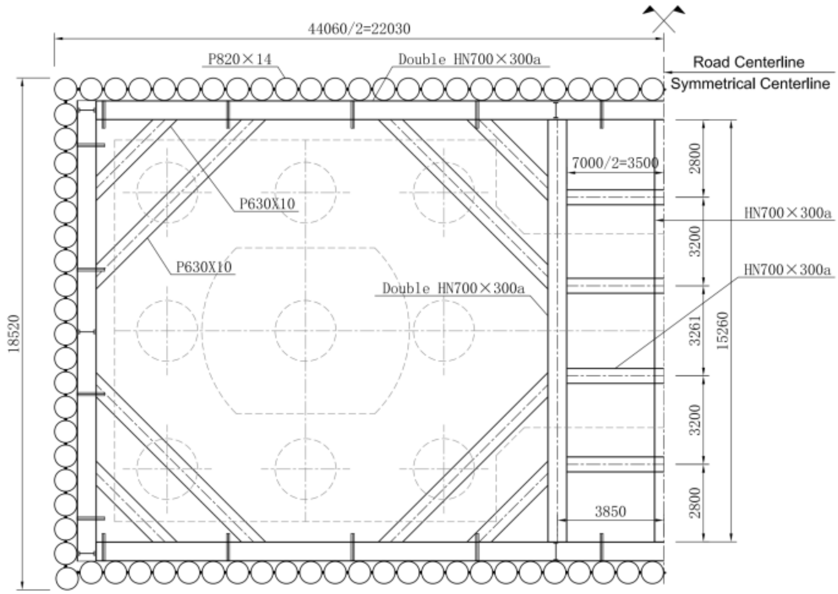
The arrangement of the interlocking steel pipe pile cofferdam for 20th pier is designed in a rectangular structure with a planar dimension of 44.06 m×18.52 m, as shown in Figure 2. The steel piles are 21 m in length, with a top elevation of 93.5 m and a bottom elevation of 73.5 m, and the pile base is embedded in moderately weathered muddy sandstone. The selected specifications for the steel pipes are Φ820×14, with both longitudinal and transverse standard spacing set at 882 mm. The interlocking mechanism of the steel pipes adopts a custom-designed "η-η" type interlock, identical in size to the SP-IV Larssen sheet pile, and is made of Q235B material.

The cofferdam is equipped with a 4-layer internal support system. The cofferdam beams utilize double-spliced HN700×300a steel, while the diagonal braces, intermediate braces, and vertical braces employ HN700×300a steel or Φ630×10 steel pipes, all made of Q235B material.

The underwater concrete base of the cofferdam uses C30 underwater concrete with a thickness of 3 m.



a) Elevation view



b) planar view

Fig. 2. Arrangement of Interlocking Steel Pipe Pile Cofferdam for 20th pier (unit: mm)

The overall construction process of the cofferdam is illustrated in Figure 3.

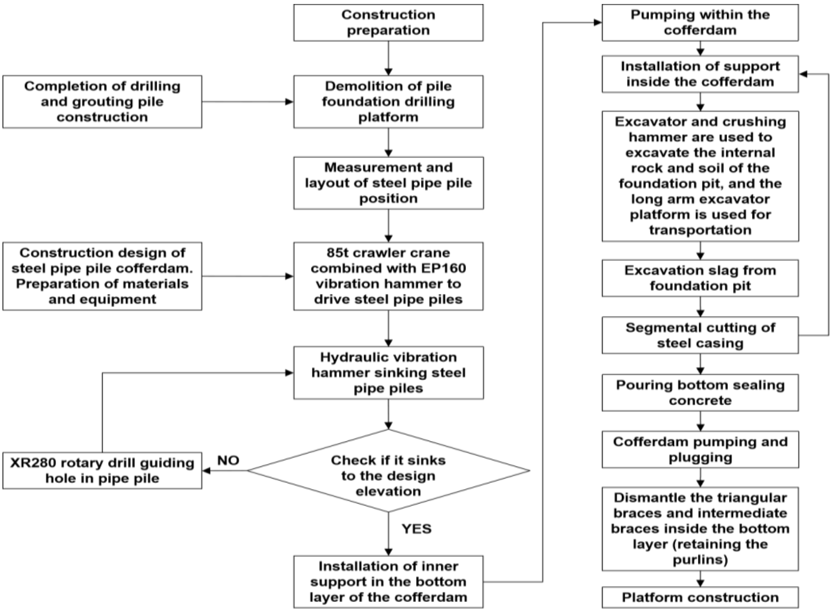


Fig. 3. Construction Process of the Interlocking Steel Pipe Pile Cofferdam for 20th pier

6 Cofferdam Calculation

6.1 Calculation Model

The overall cofferdam model was established using the finite element analysis software midas Civil. Beam elements were employed to simulate the steel pipe piles and internal supports, while solid elements were used to model the underwater concrete base. A rigid connection was assumed between the internal supports and steel pipe piles. The bottom of the steel pipe piles was restrained with fixed constraints, and the soil-structure interaction was modeled using the equivalent linear restraint method (m-value method) on the pile shaft [5]. The calculation model is depicted in Figure 4.

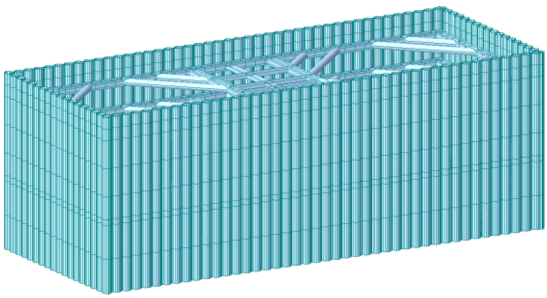


Fig. 4. Calculation Model of the Interlocking Steel Pipe Pile Cofferdam

6.2 Calculation Scenarios

Based on the construction process, the following calculation scenarios are considered:

Scenario 1: Driving steel pipe piles into the designed elevation on the steel bridge. At this point, there is no water head difference inside and outside the cofferdam. Besides self-weight, it only bears the water pressure from the incoming water surface. The water pressure is calculated based on the design water level of 92.36 m, with a corresponding water pressure acting height of 9.313 m. The flow velocity is taken as v = 2.868 m/s according to hydrological data.

Scenario 2: Underwater construction of the concrete base, reaching the required strength, and dewatering the cofferdam to create a dry working environment. At this stage, the cofferdam bears the combined effects of self-weight, static water pressure, flow water pressure, and lateral soil pressure. The water level is controlled at the design level of 92.36 m, with a corresponding height of static water pressure of 19.86 m. The calculation of flow water pressure is the same as in Scenario 1, and the lateral soil pressure is calculated with a height of 6.5 m.

Scenario 3: Independent calculation of the concrete base after dewatering the cofferdam. At this point, the concrete base, constrained by the steel pipe piles and cofferdam sidewalls, bears the buoyancy effect corresponding to the design water level of 92.36 m, along with the corresponding lateral static water pressure and soil pressure.

6.3 Calculation Results

6.3.1 Cofferdam Penetration Depth.

The depth of driving the steel pipe piles is determined based on stability calculations for preventing pipe heave and resisting uplift [5]. According to the calculations for resisting pipe heave stability, the depth of driving the steel pipe piles is 10.5 m, which is greater than 5.55 m. Based on the calculations for resisting uplift stability, the safety factor against uplift is 8.83, which exceeds the requirement of 1.8, meeting the specifications.

6.3.2 Cofferdam Buoyancy Resistance.

The buoyancy resistance of the cofferdam is calculated based on the design water level of 92.36 m. The buoyant force is 83991.8 kN. The buoyancy resistance mainly comes from the self-weight of the concrete base and the bonding force between the steel casing and the concrete. Disregarding the cofferdam's self-weight for conservative estimation, the total buoyancy resistance is 161311.2 kN. Therefore, the safety factor against buoyancy is 1.92, which is greater than 1.05, satisfying the specifications.

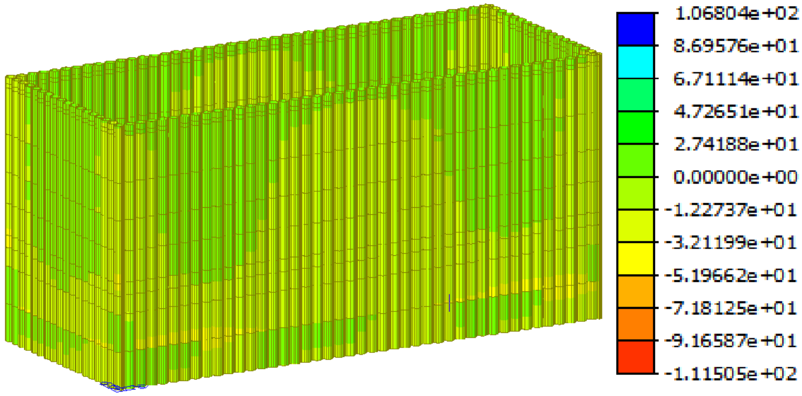
6.3.3 Cofferdam Structural Analysis.

(1) The maximum normal stress on the steel pipe piles is 111.5 MPa, as shown in Figure 5 a), which is less than 215 MPa and occurs in Scenario 2. The maximum displacement is 62.7 mm, occurring in Scenario 1. Reference values from the highway

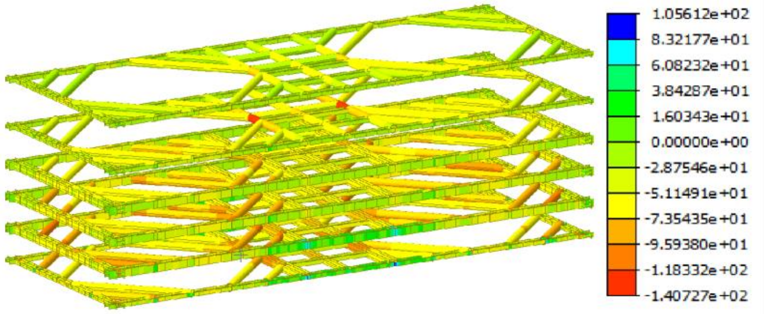
steel bridge code for cantilever beams set the displacement limit at l/300 = 21,000/300 = 70 mm. Both criteria meet the specifications.

(2) The maximum normal stress on the internal support HN700×300a steel is 140.7 MPa, as shown in Figure 5 b), which is less than 215 MPa, and the maximum normal stress on the internal support P630×10 steel is 135.1 MPa, which is less than 215 MPa. Both occur in Scenario 2 and satisfy the specifications.

(3) The calculated maximum tensile stress on the concrete base is 1.14 MPa, which is less than 1.39 MPa, and it occurs in Scenario 3, meeting the specifications.



a) normal stress diagram of steel pipe piles



b) normal stress diagram of internal supports

Fig. 5. Normal stress diagram of steel pipe piles and internal supports under basic combination action

7 Cofferdam Construction

7.1 Installation of Steel Pipe Piles

As shown in the overall cofferdam construction process (Figure 3), steel pipe piles are first driven using a tracked crane in combination with a vibratory hammer, and then a hydraulic vibratory hammer is employed to drive the piles to the specified elevation. To ensure the accuracy of the pile positions, some control piles should have guide frames set up using cast-in-place pile casings before driving [9]. If steel pipe piles encounter oversized gravel, conglomerate, or sandy mud that prevents reaching the design depth, a rotary drilling rig with a Φ 0.7 m drill rod is used to bore holes in the piles until they reach the specified elevation [10]. The sequence of pile driving is upstream side first, followed by both sides, and finally, closing at the downstream corner piles. During closure, customized interlocking steel pipe piles are fabricated based on the measured width of the closure opening.

7.2 Water Sealing of Steel Pipe Piles

The water sealing of steel pipe piles is crucial for the success of the cofferdam. After steel pipe piles are delivered to the site, it is essential to carefully clean any debris from the interlocking mechanism, inspect for deformations, and correct any deformed interlocks before use. Additionally, a leakage test should be conducted on the interlocks, and their tightness should be checked [10]. Before driving steel pipe piles, a mixture of butter and asphalt (with a weight ratio of butter: asphalt: dry sawdust: dry clay = 2: 2: 2: 1) is applied to the interlocks to reduce friction during driving.

After dewatering the cofferdam, the areas of steel pipe pile seepage should be addressed. The specific procedures are as follows:

(1) If there is localized leakage, take advantage of the suction principle generated by the water pressure difference at the leakage point. Quickly slide down a bag of dry fine sand, sawdust, or fly ash (coal ash) on the steel sheet pile at the leakage point. Under the suction effect, the filler will be drawn into the leaking joint, blocking the leakage channel.

(2) If the leakage is more severe, cut old blankets or geotextile into strips of 3 cm~5 cm. Arrange divers to plug the leakage point with the cotton strip from the water surface to the riverbed.

7.3 Installation of Internal Supports

The installation of internal supports, besides considering the forces, should also avoid hindering the installation of pier body templates. Internal supports are set from top to bottom, alternating between installing and dewatering.

7.4 Clearing the Bottom of the Cofferdam

The covering layer of the cofferdam's internal pit is composed of gravel and pebbles. Excavation can be carried out using a tracked crane in combination with a clamshell bucket. When it is challenging to excavate near the steel pipe piles and cast-in-place piles, a long-arm excavator can be used after high-pressure water jetting. For the mudstone and sandy mud inside the cofferdam, a hydraulic hammer is used for fragmentation before excavation. The excavated soil is transported to the disposal site.

7.5 Sealing the Bottom of the Cofferdam

The pouring sequence of the concrete base: lower areas first, followed by higher areas (pouring concrete in lower areas first prevents concrete from flowing downhill, causing the pipe mouth to empty or shallow burial of the pipe). Start with the perimeter and then the center, ensuring that the concrete surface is approximately horizontal.

The pouring elevation of the concrete base's top surface should be 0.1 m lower than the design elevation. After dewatering the cofferdam, a 0.1 m cushion layer is added within the bearing platform area for leveling. Water traps should be set on the inside of the steel pipe piles to prevent any slight seepage between the piles from affecting the construction of the bearing platform.

The actual construction scene before pouring the concrete base of the cofferdam is shown in Figure 6.

Fig. 6. Construction Scene of the Cofferdam

8 Conclusion

After research and analysis, the interlocking steel pipe pile cofferdam for 20th pier of the Danjiangkou Shuidu Second Bridge was selected based on design conditions. Through analysis and calculations under various scenarios, the cofferdam's penetration depth, buoyancy resistance, structural stress, and deformation all meet the requirements of the specifications, ensuring the safety and rational force of the cofferdam structure. An analysis of the critical construction techniques of the cofferdam, along with targeted technical support measures, was provided to ensure the smooth implementation of the cofferdam. The construction of the cofferdam, from driving 138 steel pipe piles to completing the pouring of the concrete base, took 92 days and successfully withstood the flood. Currently, the cofferdam has been successfully dismantled after the completion of the substructure construction. The design, structural form, and construction methods of this cofferdam can serve as a reference for similar projects.

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