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Application of Steel Sheet Pile Cofferdam in the Construction of Transition Pier Bearing Platform of Hongshui River Bridge

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Abstract: As a common cofferdam support construction technology, steel sheet pile provides a construction platform for the construction of Underwater Bridge Foundation and a guarantee for construction safety. Therefore, the importance of construction analysis and construction checking calculation of steel sheet pile cofferdam is self-evident. This paper takes the transition pier cap of Hongshui River Bridge in China as an example. Firstly, the whole construction process of steel sheet pile cofferdam is discussed, and the key and difficult points in the construction process are analyzed. The key points of quality control are formulated around the construction processes such as the installation of guide frame, the insertion and driving of steel sheet pile and the installation of purlin support, and the key construction technologies to prevent the leakage of cofferdam are studied. The possible problems in construction are summarized and the corresponding measures are given. On this basis, the structural stress of steel sheet pile cofferdam is discussed, and the most unfavorable load is combined according to the construction and stress of cofferdam. Finally, the structural analysis and checking calculation of steel sheet pile are carried out. The checking calculation methods include traditional calculation method and finite element method. Based on this, the safety evaluation of its construction is carried out, and the safety and stability of steel sheet pile cofferdam construction are verified.

Keywords: Steel Sheet Pile Cofferdam, Construction Technique, Structural Checking Calculation, Finite Element Simulation, Construction Safety

1. Introduction

In recent 50 years, China has vigorously developed bridge construction, and steel sheet pile cofferdam has made great progress in construction practice [1-4]. As a temporary support structure, steel sheet pile cofferdam has good waterproof performance, convenient construction technology, wide adaptability and can be reused after demolition. It is widely used in foundation construction [5, 6]. The principle is that the steel is processed to form a steel pipe or steel plate, which is driven into the underwater soil layer, and the adjacent pile bodies are spliced to form a continuous structure with certain strength and water resistance, or the prefabrication and assembly are completed on the shore and sent to the pier position by means of floating transportation. The steel sheet pile cofferdam has fast construction speed and large section stiffness. It can be applied to various complex strata and has good economic and social benefits [7].

In recent years, many achievements have been made in the checking calculation of structural stability of steel sheet pile cofferdam. Sun [8] divided the construction into three typical working conditions and checked the strength of sheet pile, support system and purlin respectively. It is proved that the strength, support stability, anti uplift stability and embedded stability of steel sheet pile cofferdam meet the requirements of relevant specifications; Taking Haihe Bridge as an example, Liang et al. [9] established the construction monitoring system of steel sheet pile cofferdam. The results show that the measurement results are basically consistent with the calculation results of finite element software. Xia et al. [10] took the Pearl River Bridge as the background and analyzed the structural strength and stability under different working conditions by using the finite element software ANSYS. Xiong et al. [11] calculated the earth pressure on the cofferdam and monitored the stress during construction. The results showed that the difference between the two was within the allowable error range. Yang et al. [12] analyzed the stress and strain of the cofferdam bottom sealing concrete through the finite element software ANSYS to ensure the safe progress of the project. Therefore, checking the stress state of steel sheet pile cofferdam under various working conditions is the key to ensure its safety and quality in construction.

Taking Hongshui River Bridge as an example, this paper describes the construction process of steel sheet pile in detail, analyzes the stress state of steel sheet pile cofferdam under different working conditions, and then combines the most unfavorable load. At the same time, the soil depth of steel sheet pile, the combined stress of purlin and support, shear stress and axial compressive stress of inner support under different working conditions of steel sheet pile cofferdam are modeled and checked. Finally, check the anti uplift stability of foundation pit and the anti piping stability of foundation pit. The structural checking calculation of steel sheet pile cofferdam is of great significance to the construction safety of pier cap.

2. Project Overview and Design Parameters

2.1. Project Overview

Hongshui River Bridge is a special bridge in China. Due to the construction requirements of transition pier bearing platform, in order to prevent water pollution and ensure no water and soil loss, steel sheet pile cofferdam needs to be built. The depth of the foundation pit is 5.3m, which is almost land construction after filling. U-shaped steel sheet piles are used for support.

The main bridge of Hongshui River Bridge is a prestressed concrete continuous rigid frame bridge (65+2×120+65m), 5#/9# transition pier is located on the Bank of Hongshui River, and the integral bearing platform is adopted. The foundation pile adopts 2.5m diameter bored pile. The structural diagram of transition pier bearing platform is shown in Figure 1.

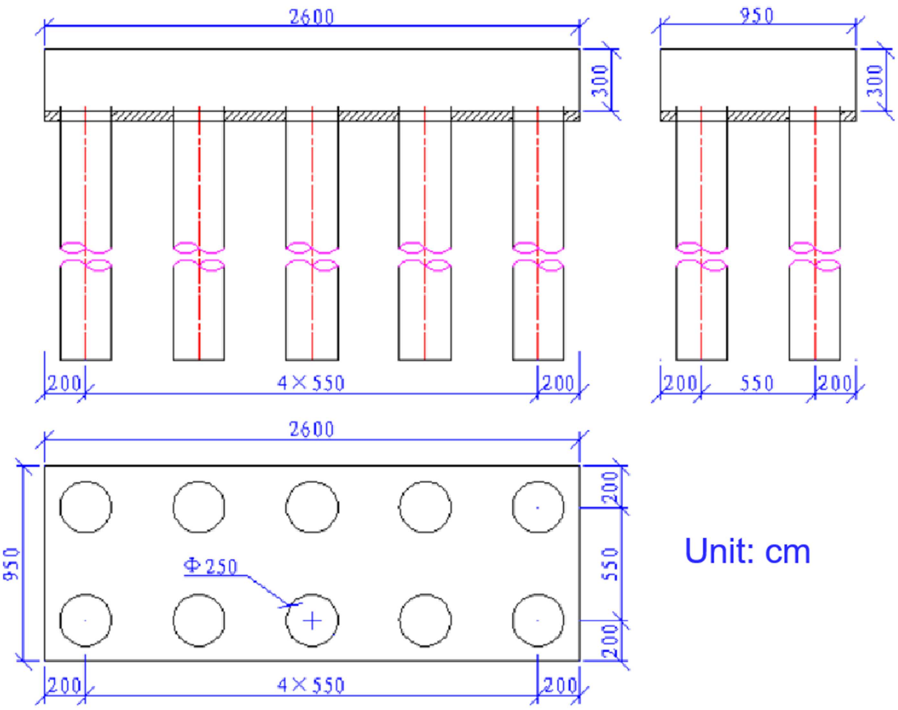

Figure 1. *Structural diagram of transition pier bearing platform.*

The Hongshui River Bridge is located at the upstream of Longtan Hydroelectric power stations, belonging to the Pearl River system, with developed surface water. The normal pool level (high water level) + 223m. In flood season (may ~ August), in order to reduce the loss of farmland inundation on both banks of the river, it is lowered to the limited water level + 219M (low water level) for operation; The operation shall not exceed + 221.5m in September, and return to normal pool level at the end of flood season and October. The main stratum of the project is the residual slope deposits of the Quaternary gravelly soil, and the underlying bedrock is mainly composed of Triassic limestone mixed with silty mudstone, Permian siliceous mudstone mixed with mudstone and sandstone. There is no adverse geological distribution at the bridge site. The ground elevation of the 5# pier of Hongshui River Bridge is + 219.5m, and the soft plastic clay layer is about 19m deep below the ground. The ground elevation of the 9# pier is + 218.5m, and the plastic clay layer is about 10.5m deep below the ground. The elevation of the platform top after backfilling and rolling at the two pier positions is + 224m. At the same time, laterite is used to backfill and roll the island to form a drilling platform to provide a site for the construction of transition pier cushion cap.

2.2. Design Parameters

The index value of soil layer, design parameters of steel sheet pile cofferdam, size and section characteristics of U-shaped steel sheet pile are shown in Table 1, table 2 and table 3 respectively.

Table 1. *Index value of soil layer.*

Soil type	Saturated bulk density γ (KN/m³)	Cohesion c (KPa)	internal friction angle φ (°)
Backfill laterite	20	25	20
Plastic clay	20	10	15
Soft plastic clay	18	10	15

Table 2. *Design parameters of steel sheet pile cofferdam.*

project	Value
Design value of tensile (compressive) and bending combined stress of Q235A steelQ235a	215MPa
Design value of shear strength of Q235A steel	125MPa
Design value of combined tensile (compressive) and bending stress of Q345 steel	310MPa
Design value of shear strength of Q345 steel	180MPa
Partial factor of load	1.4soil pressure+1.0Self weight of structure

Table 3. *Dimensions and section characteristics of U-shaped steel sheet pile.*

Section size			Single root parameter				Wall parameters per meter			
Effective width	Effective height	Web thickness	Sectional area	theory weight	Moment of inertia	section modulus	Sectional area	Theoretical weight	Moment of inertia	section modulus
B	H	t	Area A	W	I_x	Z_x	Area A	W	I_x	Z_x
mm	mm	mm	cm^2	kg/m	cm^4	cm^3	cm^2/m	kg/m^2	cm^4/m	cm^3/m
400	125	13	76.42	60	2220	223	191	149.9	16800	1340

3. Construction Process of Steel Sheet Pile

3.1. Installation of Guide Frame

During the construction, the steel sheet pile can be driven only after the guide frame composed of guide beam and guide column is set [13]. Guide frame is a key factor to ensure the quality of pile driving, which needs to have sufficient hardness and strength. When installing the guide frame, the specific position of the guide beam shall not interfere with the steel sheet pile. Reasonably use the level or total station to appropriately adjust and control the position of the guide beam.

3.2. Steel Sheet Pile Driving

In the construction process, the most critical process is inserting and driving steel sheet piles. Before inserting and driving steel sheet piles, the specific location of pile driving shall be clearly marked. The position of the steel sheet pile in the middle is vertical, and the two sides are guided by welded angle steel, so as to ensure that there is no offset during pile sinking. The key construction points of adjustment and closure, integrity of pile insertion, dispersion and immediate correction shall be strictly observed when inserting and driving steel sheet piles [14].

3.3. Install the Inner Support

Steel transverse compression beam and steel pipe support method are adopted to support both sides of the foundation trench. The design drawing specifies the position of steel belt beam, including vertical distance. The beam position shall be determined first, and then the I-beam shall be installed 1m below the steel support by layered excavation method. The steel section and steel section shall be connected by welding. The distance between each steel section shall be kept at 2.5m, and relevant water pumping and water leakage prevention work shall be done in time.

3.4. Cofferdam Pumping and Seepage Prevention

Before construction, the steel sheet pile shall be subject to leakage detection, especially at the lock mouth. The tightness test shall be carried out on the pile at an interval of 1~2m to check its compactness. In case of leakage during construction, if it is relatively minor, it can be treated after the completion of precipitation. If the leakage point is at the lock port, it can be blocked with clay [15]. When the leakage is serious and the water level is deep, plugging agent or sandbag can be used to stop the leakage. Before driving into the steel sheet pile cofferdam, the butter and sawdust shall be mixed and coated on the locking device to reduce the resistance and improve the anti leakage performance. If there is still water leakage in the lock, lint must be used to block the inside of the lock to further reduce the impact of water pressure on the steel sheet pile. When pumping water, the mixture of sawdust and slag shall be sprayed on the external water leakage.

3.5. Underwater Back Sealing Control

The construction method of block pouring shall be adopted for the bottom sealing concrete, and the underwater concrete conduit shall be arranged within the cofferdam [16]. During concrete pouring, the quality of conduit joints shall be controlled, and the quality and quantity of joints shall be well controlled to meet the requirements of continuous pouring [17]. The order of the back cover is from the periphery to the middle, and the ball is opened and sealed in turn. The flow direction of the distributed concrete shall be controlled according to the rise of the concrete top surface, so that the concrete can meet the conditions of uniform rise within the cofferdam. Underwater concrete pouring needs to focus on height difference control and observe the diffusion of concrete. Before the conduit is displaced, it is necessary to ensure that the concrete in the pouring area is fully paved to prevent missing pouring.

The underwater concrete pouring height shall be controlled at 20cm below the bearing platform, and the concrete strength shall be tested. When the concrete strength meets the design requirements, if the cofferdam pumping operation is completed, the formwork shall be erected on the upper part of the bottom sealing concrete, and the 20cm thick concrete shall be used as the leveling layer. Before the final back sealing, professional technicians shall be designated to inspect the specific conditions of the base to meet the expected pouring requirements. The construction flow chart is shown in Figure 2 below.

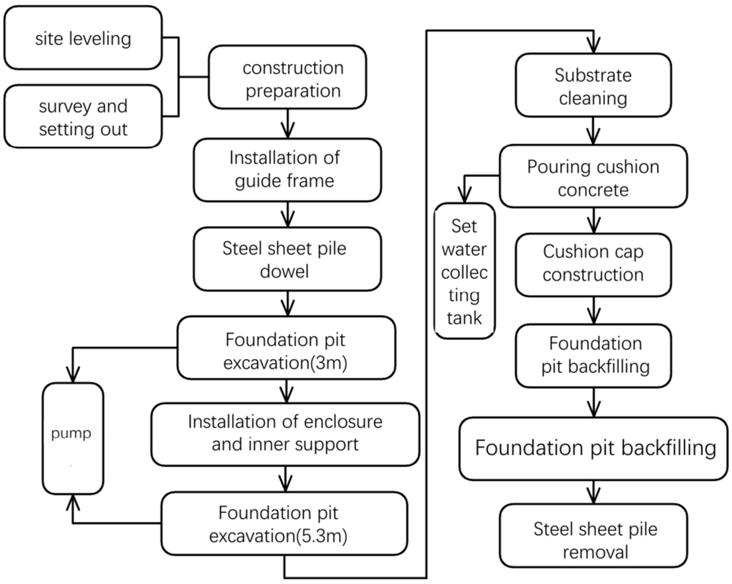

Figure 2. *Construction flow chart of steel sheet pile cofferdam.*

4. Working Condition Analysis and Load Combination

According to different construction conditions and cofferdam stress conditions, it can be divided into four representative working conditions, and then the most unfavorable loads can be combined. See table 4 below.

Table 4. *Working conditions and load combinations.*

working condition	**Working condition description**	**Most unfavorable load combination**	**Checking part**
Working condition I	The guide device is used to drive the steel sheet pile. After the driving, the foundation pit is excavated to a depth of 3m	Overload outside the pit (31KN/m^2)+1.4 active earth pressure	Strength and stiffness of steel sheet pile
Working condition II	Install the enclosure and inner support 1.3m away from the top of the steel sheet pile, and continue to excavate the foundation pit for 5.3m	Overload outside the pit (31KN/m^2)+1.4 active earth pressure	Strength and stiffness of steel sheet pile, strength and stiffness of enclosure and inner support, stability of foundation pit
Working condition III	Pour 0.5m cushion concrete and set water collecting tank	Overload outside the pit (31KN/m^2)+1.4 active earth pressure	Strength and stiffness of steel sheet pile, strength and stiffness of enclosure and inner support, stability of foundation pit
Working condition IV	The foundation pit shall be backfilled to the top elevation of the bearing platform (1.8m from the top of the steel sheet pile), and the enclosure and inner support shall be removed	Overload outside the pit (31KN/m^2)+1.4 active earth pressure	Strength and stiffness of steel sheet pile

Through the above analysis of working conditions, it can be seen that working conditions I and II are the most unfavorable working conditions. Working conditions 3 and 4 are relatively safe, so there is no need to conduct stress analysis and recheck calculation for these two working conditions.

5. Structural Checking Calculation

In this paper, the geotechnical analysis software is used to analyze and check the steel sheet pile. According to the elastic-plastic common deformation theory of pile and soil, 1m plate width is taken for calculation. The calculated value of the reaction force of the inner support is loaded on the prison and the inner support structure, and then the finite element analysis method is used to calculate the prison and the inner support.

5.1. Calculation of Penetration Depth of Steel Sheet Pile

According to the "equivalent beam method", the penetration depth of steel sheet pile is calculated. The earth pressure calculation formula is:

$$P_a = \gamma hK_a - 2c\sqrt{K_a}, K_a = \tan^2(45° - \phi/2) \quad (1)$$

$$P_p = \gamma hK_p + 2c\sqrt{K_p},\ K_p = \tan^2(45° + \phi/2) \quad (2)$$

Where Pa is the active earth pressure, KPa; Pp is the passive earth pressure, KPa; γ is the gravity of soil, KN/m^3; h is the depth at the calculation point, m; K_a is the active earth pressure coefficient; K_p is the passive earth pressure coefficient; φ is the internal friction angle of soil, (°).

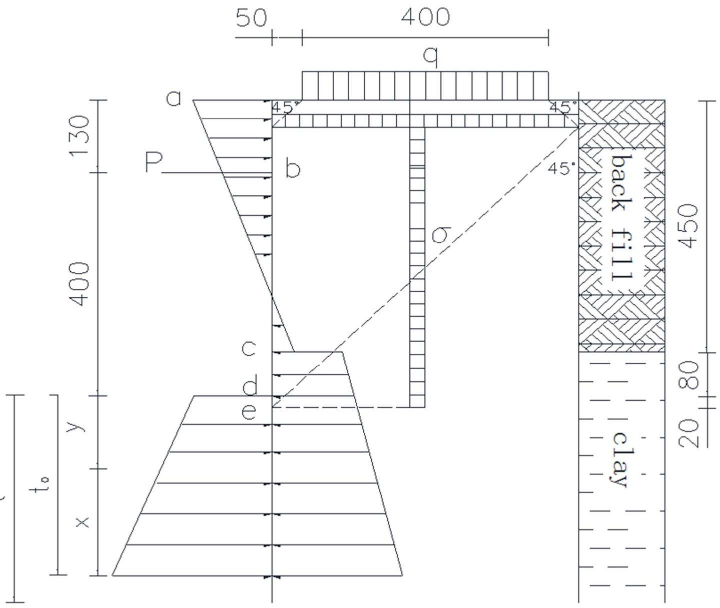

Figure 3. *Calculation diagram of steel sheet pile penetration depth.*

Active earth pressure value of backfill A and C points:

$$P_{a1} = 2c_1\sqrt{K_{a1}} = 35KN/m^2;$$

$$P'_{a1} = \gamma_1 h_1 K_{a1} - 2c_1\sqrt{K_{a1}} = 9KN/m^2;$$

Active earth pressure at point c of undisturbed soil: $P_{a2} = \gamma_1 h_1 K_{a2} - 2c_2\sqrt{K_{a2}} = 37.6KN/m^2$;

Active earth pressure at point d of undisturbed soil: $P'_{a2} = (\gamma_1 h_1 + \gamma_2 h_2)K_{a2} - 2c_2\sqrt{K_{a2}} = 46.1KN/m^2$;

Passive earth pressure value of undisturbed soil point d:

$$P_{p2} = 2c\sqrt{K_{p2}} = 26.1KN/m^2,$$

The overload Q outside the pit is transformed into the load on the steel sheet pile:

$$\sigma = \frac{qbl}{(b+2a)(l+2a)} = \frac{25\times4\times5}{(4+1)(5+1)} = 16.7KN/m^2 \quad (3)$$

Where b is the width of the load outside the pit, l is the height acting on the steel sheet pile, and a is the distance from the load outside the pit to the edge of the foundation pit.

Active earth pressure at point e:

$$P''_{a2} = (\gamma_1 h_1 + \gamma_2 h'_2)K_{a2} - 2c_2\sqrt{K_{a2}} = (20\times4.5+18\times1)\tan^2 37.5° - 20\times\tan 37.5° = 48.2KN/m^2$$

Passive earth pressure at point e:

$$P'_{p2} = 18\times0.2\times\tan^2 52.5° + 20\times\tan 52.5° = 28.2KN/m^2$$

It can be seen that the passive earth pressure at this point is less than the active earth pressure, so the pressure zero point occurs below point e.

$$P_a = P_b \Rightarrow \left[20\times4.5+18\times(0.8+y)\right]\tan^2 37.5^\circ - 20\tan 37.5^\circ = 18y\tan^2 52.5^\circ + 20\tan 52.5^\circ \Rightarrow y = 1m$$

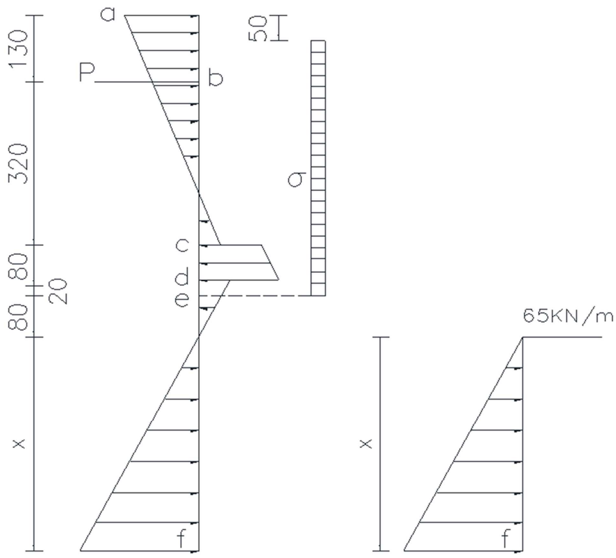

Figure 4. Analysis diagram of "equivalent beam method".

For beam section x, it can be known from the moment balance of point G at the bottom of the beam and the linear relationship of earth pressure:

$$\left.\begin{array}{l}\sum M_f = 0 \\ \frac{20}{1}=\frac{P_f}{x} \Rightarrow P_f = 20x\end{array}\right\} \Rightarrow x = 4.4m\ ,$$

Penetration depth t= (1.1~1.2) t_0= (1.1~1.2) × (1+4.4)=5.9~6.5m<6.7m, meet the requirements.

5.2. Strength Calculation of Steel Sheet Pile

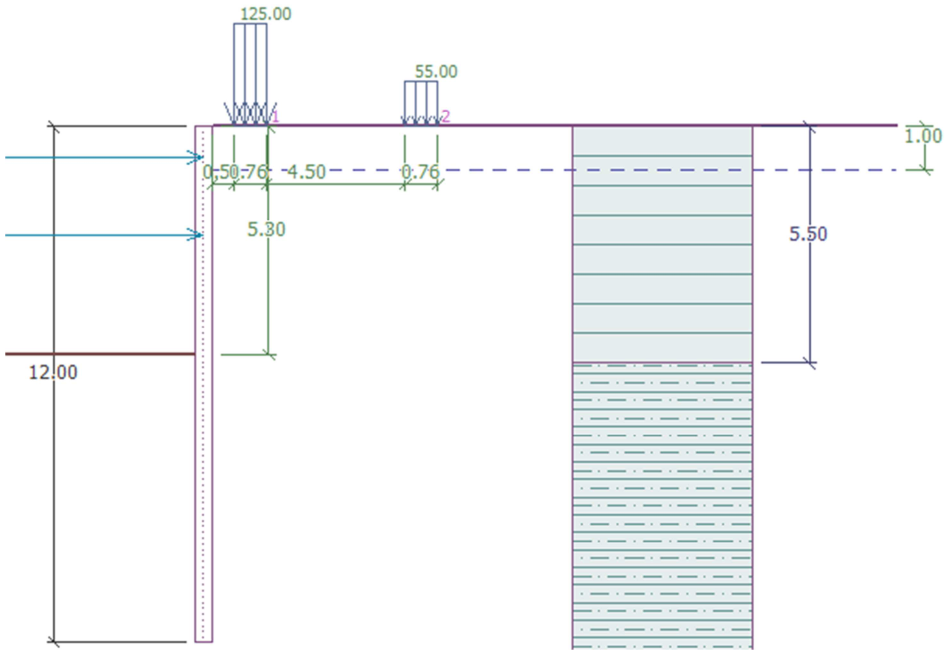

Figure 5. Calculation model.

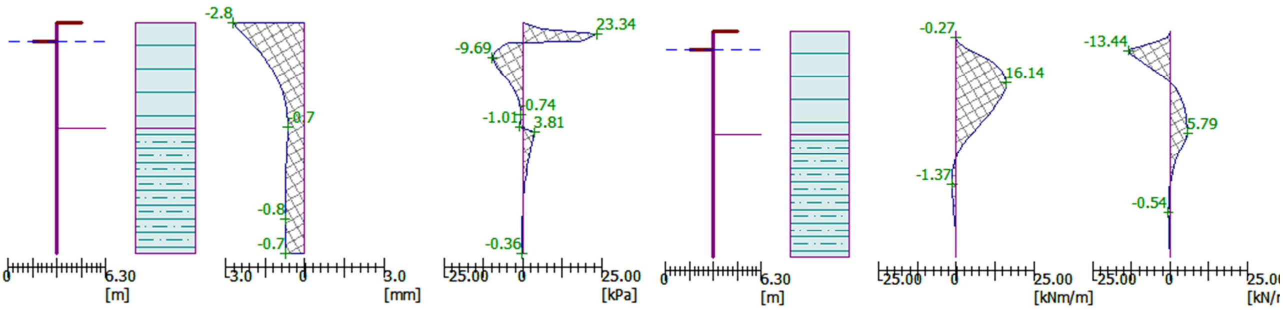

Figure 6. Calculation structure of working condition I.

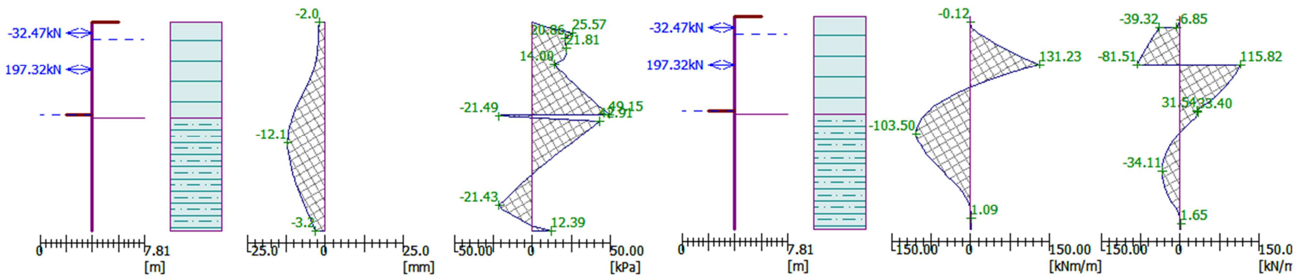

Figure 7. Calculation structure of working condition II.

Table 5. Summary of calculation results.

working condition	displacement (mm)	bending moment (kN·m/m)	Shearing force (KN/m)	Reaction force of top enclosure (KN/m)	Bottom enclosure reaction (KN/m)
Working condition I	2.8	16.1	13.4		
Working condition II	12.1	131.2	115.8	-32.5	197.3

In the above calculation results, the maximum bending moment of steel sheet pile is M_{max} = 131.2kN·m/m, The maximum shear force is V_{max}=115.8kN/m. When checking the strength of steel sheet pile, the stress is $\sigma = M_{max}/W =$ 98MPa<310MPa, The shear stress is $\tau = V_{max}/A =$ 61MPa<180MPa, meet the requirements.

5.3. Checking Calculation of Enclosure and Inner Support

The reaction value of the top-level enclosure is 33.1kn/m, and the reaction value of the bottom-level enclosure is 73kn/m. add the load to the enclosure and check the enclosure and inner support.

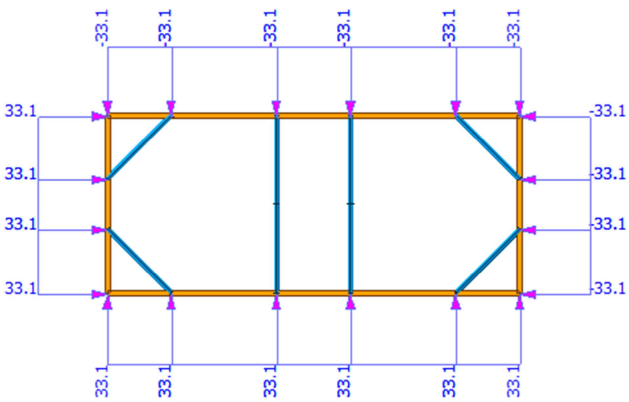

Figure 8. Calculation model diagram of the first fence and inner support.

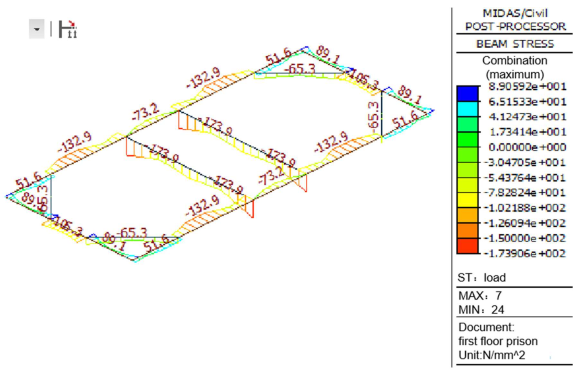

Figure 9. Tension/bending combined stress diagram of the first fence and inner support.

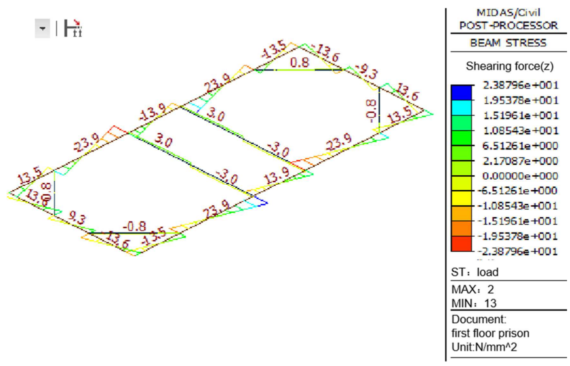

Figure 10. Shear stress diagram of the first fence and inner support.

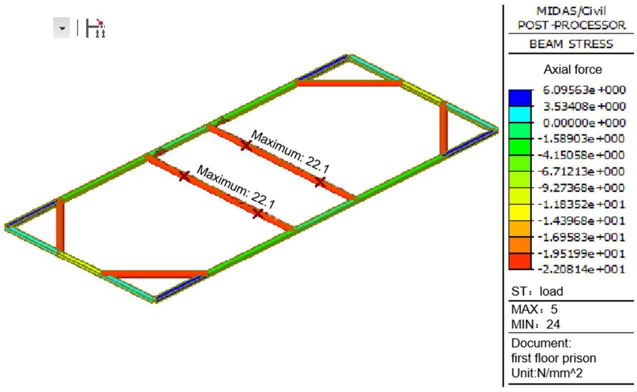

Figure 11. *Tension/compression stress diagram of the first fence and inner support.*

According to the calculation, the maximum combined stress of the first prison and inner support is 174MPa, which is less than the design value of tensile, flexural and compressive strength [f] 215MPa, as shown in Figure 9. The shear stress of the prison and inner support is 24MPa, which is less than the design value of shear strength [f] 125MPa, as shown in Figure 10. Slenderness ratio of steel pipe is $\lambda = \frac{\mu l}{i} = \frac{12500}{150} = 83$, corresponding stability coefficient φ=0.763, then the stability allowable stress is $\varphi[\sigma]=164Mpa$, The inner support meets the stability requirements.

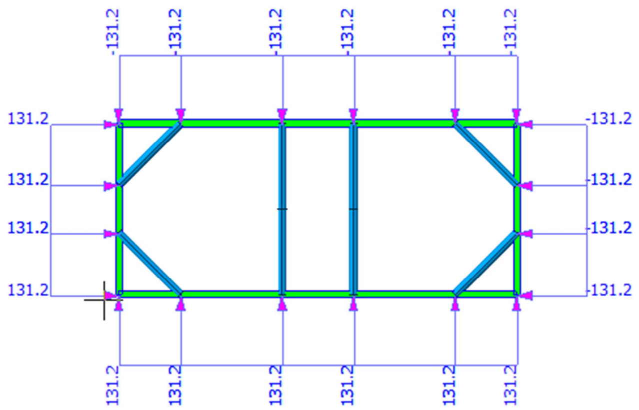

Figure 12. *Calculation model diagram of the second fence and inner support.*

According to the calculation, the maximum combined stress of the second prison and inner support is 190MPa, which is less than the design value of tensile, flexural and compressive strength [f] 215MPa, as shown in Figure 13. The shear stress of the prison and inner support is 51MPa, which is less than the design value of shear strength [f] 125MPa, as shown in Figure 14. Slenderness ratio of steel pipe is $\lambda = \frac{\mu l}{i} = \frac{12500}{220} = 57$, corresponding stability coefficient φ=0.894, then the stability allowable stress is $\varphi[\sigma]=192Mpa$, The inner support meets the stability requirements.

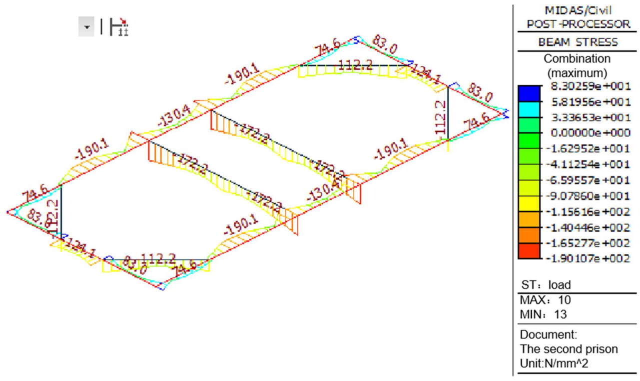

Figure 13. *Tension/bending combined stress diagram of the second fence and inner support.*

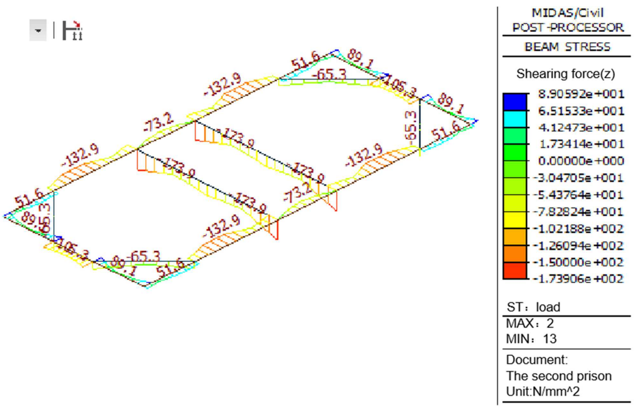

Figure 14. *Shear stress diagram of the second prison and inner support.*

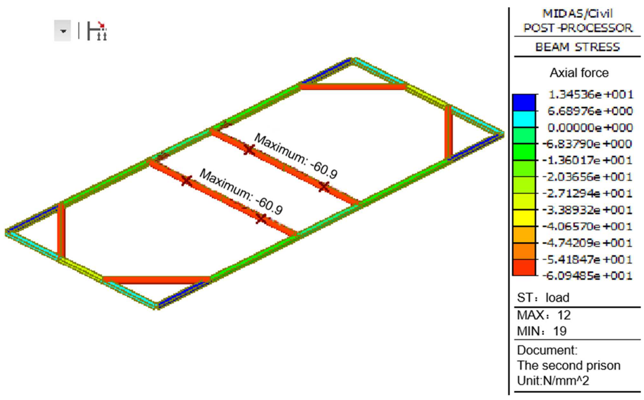

Figure 15. *Tensile stress diagram of the second fence and inner support.*

Table 6. *Summary of calculation results.*

Enclosure and inner support	Tension bending combined stress (MPa)	Shear stress (MPa)	Axial compressive stress of inner support (MPa)
The first floor (2I36a/φ430×6)	174	24	22
The second floor (2I56a/φ630×8)	190	51	61

5.4. Checking Calculation of Anti Uplift Stability of Foundation Pit

Uplift refers to the phenomenon of foundation imbalance when the pressure composed of column structure and other structures is greater than the bearing capacity of the foundation. The main factors causing foundation pit uplift are as follows [18, 19]:

(1) After foundation pit excavation, the rebound deformation of the lower soil and the expansion deformation under the action of rainwater.

(2) The overall instability of the supporting structure kicks its bottom out to the pit bottom, resulting in the uplift of the soil at the pit bottom.

The national standard specification stipulates that the buried depth of Anchor Pull or support support structure shall comply with the following provisions. The calculation can be checked according to the following formula:

$$\gamma_{m1} = 20kN/m^3 \tag{4}$$

$$\gamma_{m1} = 20kN/m^3 \tag{5}$$

$$\gamma_{m1} = 20kN/m^3 \tag{6}$$

Among them, the safety factor against uplift is taken as 1.6 for this structure; $\gamma_{m1} = 20kN/m^3$ is the weight of the soil above the ground of the retaining member outside the foundation pit (KN/m^3), taken as $\gamma_{m1} = 20kN/m^3$; $\gamma_{m2} = 20kN/m^3$ is the weight of the soil above the ground of the retaining member in the foundation pit (KN/m^3), taken as $\gamma_{m2} = 20kN/m^3$; D is the thickness of soil layer from the bottom of foundation pit to the bottom of retaining member (m), $D = 6.7m$; $h = 5.3m$ is the depth of foundation pit (m), $h = 5.3m$; $q_0 = 125kN/m^2$ is the uniformly distributed load on the ground (KPa), $q_0 = 125kN/m^2$; $c = 11kPa$ is the bearing capacity coefficient; $c = 11kPa$ is the cohesion of the soil below the bottom of the retaining member $c = 11kPa$ 、 internal friction angle $\phi = 15°$.

$$N_q = tg^2(45° + \frac{15}{2})e^{\pi \tan 15} = 3.94;$$
$$N_c = (N_q - 1)/\tan 15 = 11$$

$$\frac{\gamma_{m2}DN_q + cN_c}{\gamma_{m1}(h+D) + q_0} = \frac{20\times6.7\times3.94 + 11\times11}{20\times12 + 125} = 1.78 \ge 1.6$$

Therefore, the basement will not bulge.

5.5. Checking Calculation of Anti Piping Stability of Foundation Pit

Pressurized water flow, fine soil particles and pipes are the three necessary conditions for piping at the bottom of the foundation pit. When the piping is serious, the foundation pit will be damaged [20]. The piping phenomenon is related to the soil environment. The way to solve the piping problem is to place steel sheet piles in saturated soil. The piping stability is checked by the following formula [21]:

$$K = \frac{(h + 2t)\gamma'}{h\gamma_w} \tag{7}$$

Where, h is the distance between groundwater and pit bottom; t is the penetration depth of the pile; γ' is the floating weight of soil; γ_w is the gravity of water; K is the anti piping safety factor (1.5 ~ 2.0). The calculated k = 3.6 indicates that piping will not occur.

6. Conclusion

In this paper, the problems existing in the research of steel sheet pile cofferdam are analyzed combined with the engineering example of Hongshui River Bridge. Firstly, the construction method of steel sheet pile cofferdam is summarized, and the most typical working condition is selected for analysis in combination with the actual situation. Then the finite element software is used to model the steel sheet pile structure. Finally, the mechanical characteristics and stability of the structure are explored. The results show that the safety of the cofferdam structure and the stability of the foundation pit are effectively guaranteed to meet the requirements of on-site construction. At the same time, it provides an effective reference for the construction of similar engineering structures.

In the future research, it is suggested that researchers put forward higher requirements for the real-time monitoring and control during the construction of steel sheet pile cofferdam, and deeply consider the actual load borne by the foundation. It mainly includes: actual soil depth, actual water velocity, actual water pressure, etc. Through comprehensive consideration of the influence of various factors and accurate calculation, the accurate and real stress condition of cofferdam structure can be obtained to ensure the safety of construction.

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