Design and Construction

Mechanical Behavior Analysis of the Pile Cap for the Main Pylon of an A-Shaped Cable-Stayed Bridge

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Abstract: To investigate the mechanical behavior of the pile cap for the main pylon of an A-shaped cable-stayed bridge without crossbeams, a realistic bridge of this type was selected as a case study. A grillage finite element model of the entire bridge was established using MIDAS to compare and analyze the effects of three different pile foundation layout schemes on the mechanical response of the pile cap. Subsequently, a local solid model of the pile cap was developed using MIDAS FEA NX to examine its transverse stress distribution under frequent load combinations. The results of comparison and selection revealed that the optimal scheme involves symmetrically arranging "2+2" piles at the dumbbell-shaped necking region in the center of the pile cap. This configuration effectively reduces the span, resulting in a more uniform and reasonable distribution of stress and deformation in the pile cap under frequent load combinations. The load-bearing mechanism of the pile cap is characterized by transverse prestressed steel tendons acting as key "balancing elements". By establishing a prestress field within the pile cap, these tendons directly resist the horizontal thrust generated by the pylon, working together with the passive pile foundation to form a three-dimensional load-bearing system that internally balances, spatially distributes, and transfers the complex spatial forces from the superstructure. In addition, reinforcement meshes should be arranged in the prestress anchorage zones and in the regions between piles at the bottom of the pile cap to resist local tensile stress concentrations and control cracking. Traditional spatial grillage models exhibit limitations in analyzing the mechanical behavior of the thick and large pile caps in such A-shaped pylons, which may lead to distorted results and overestimation of local stresses. Therefore, the use of solid finite element models is recommended for accurate verification and design.

Keywords: A-shaped cable-stayed bridge; main pylon; pile cap; mechanical behavior; finite element analysis

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1 Introduction

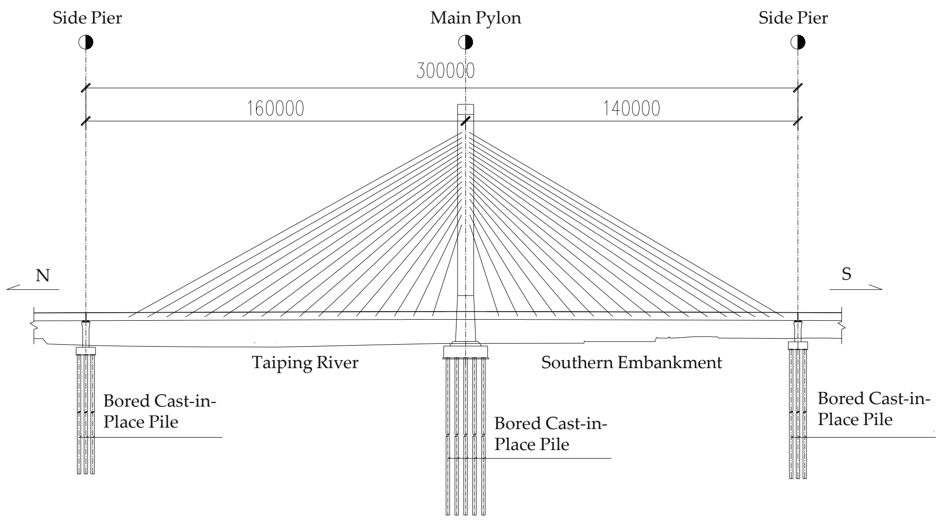
With the demands of economic development, transportation engineering increasingly requires long-span bridges. Cable-stayed bridges are widely used in long-span bridge structures because of their large span, good wind resistance, and relatively simple structure [1,2]. Current road planning often requires wider bridge decks. To accommodate wide main girders, deck height is often restricted, leading to the application of A-shaped pylons in practical engineering [2-4].

In the absence of crossbeams to balance the outward horizontal tension and bending moment of A-shaped pylons, the pile cap must not only withstand the vertical forces and bending moments transferred from the piles and the pylon but also resist the outward horizontal thrust and additional bending moments from the pylon. This results in complex stress conditions, making the analysis of force transfer mechanisms a key issue in the design of such cable-stayed bridges. Wang [2] conducted an overall analysis of A-shaped cable-stayed bridge structures, providing a reference for the design of similar ultrawide single-pylon cable-stayed bridges. Xu [3] investigated the mechanical behavior of bracing systems during the construction of A-shaped pylons. Li et al. [4] studied the effects of temperature variations on the construction of A-shaped pylons. These studies have investigated aspects such as overall design, construction techniques, and temperature effects for A-shaped pylons. Zheng et al. [5] analyzed the bearing capacity of the normal section of pile caps for A-shaped pylons using the "strut-and-tie" model and evaluated their punching shear capacity according to design specifications. Song [6] established both grillage and three-dimensional solid models for the main pylon pile cap of a diamond-shaped cable-stayed bridge and investigated the stress distribution of the pile cap under the force transfer from inclined legs of the diamond-shaped pylon and the reaction distribution of the pile foundation. The results indicated that grillage models based on beam theory have limitations in analyzing monolithic pile caps subjected to inwardly inclined forces. Pan et al. [7] studied the crack resistance of mass concrete in the main pier pile cap of a cable-stayed bridge by applying hydration heat control materials to mitigate temperature-induced cracking. Wen [8] investigated the influence of hydration heat parameters on the temperature and stress fields of mass concrete pile caps. Based on the current research, although considerable attention has been given to pile caps for pylons with crossbeams, studies specifically focusing on pile caps for A-shaped pylons without crossbeams remain limited. In such cases, when the pile cap effectively replaces the structural function of the crossbeam by resisting horizontal transverse thrust from the pylon, complex stress conditions are created. Therefore, further investigation is necessary.

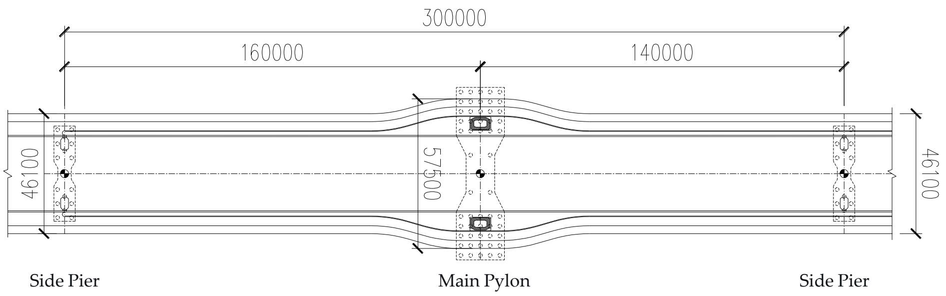
In this paper, an actual single-pylon spatial double-cable-plane cable-stayed bridge is used as the engineering background. A grillage finite element model of the entire bridge is developed using MIDAS to analyze and compare the effects of three different pile foundation layout schemes on the mechanical response of the pile cap. In addition, a local solid finite element model of the pile cap is developed using FEA NX finite element software to investigate its stress distribution under frequent load combinations. The results provide useful insights and can serve as a reference for the design of similar engineering projects.

2 Project Background

The bridge is a single-pylon, spatial double-cable-plane cable-stayed bridge with span lengths of (160 + 140) m and a deck width ranging from 46.1 m (standard section) to 57.5 m (widest section near the pylon). It adopts a semifloating system, as shown in Figure 1. The main pylon is a reinforced concrete "A-shaped" pylon with a total height of approximately 102.75 m. The pile cap is transversely continuous and serves as a transverse crossbeam. The substructure consists of bored cast-in-place piles with a diameter of φ1.5 m, as illustrated in Figure 2.



a) Elevation



b) Plan

Figure 1 General layout of the Zhongxing Bridge (unit: mm)

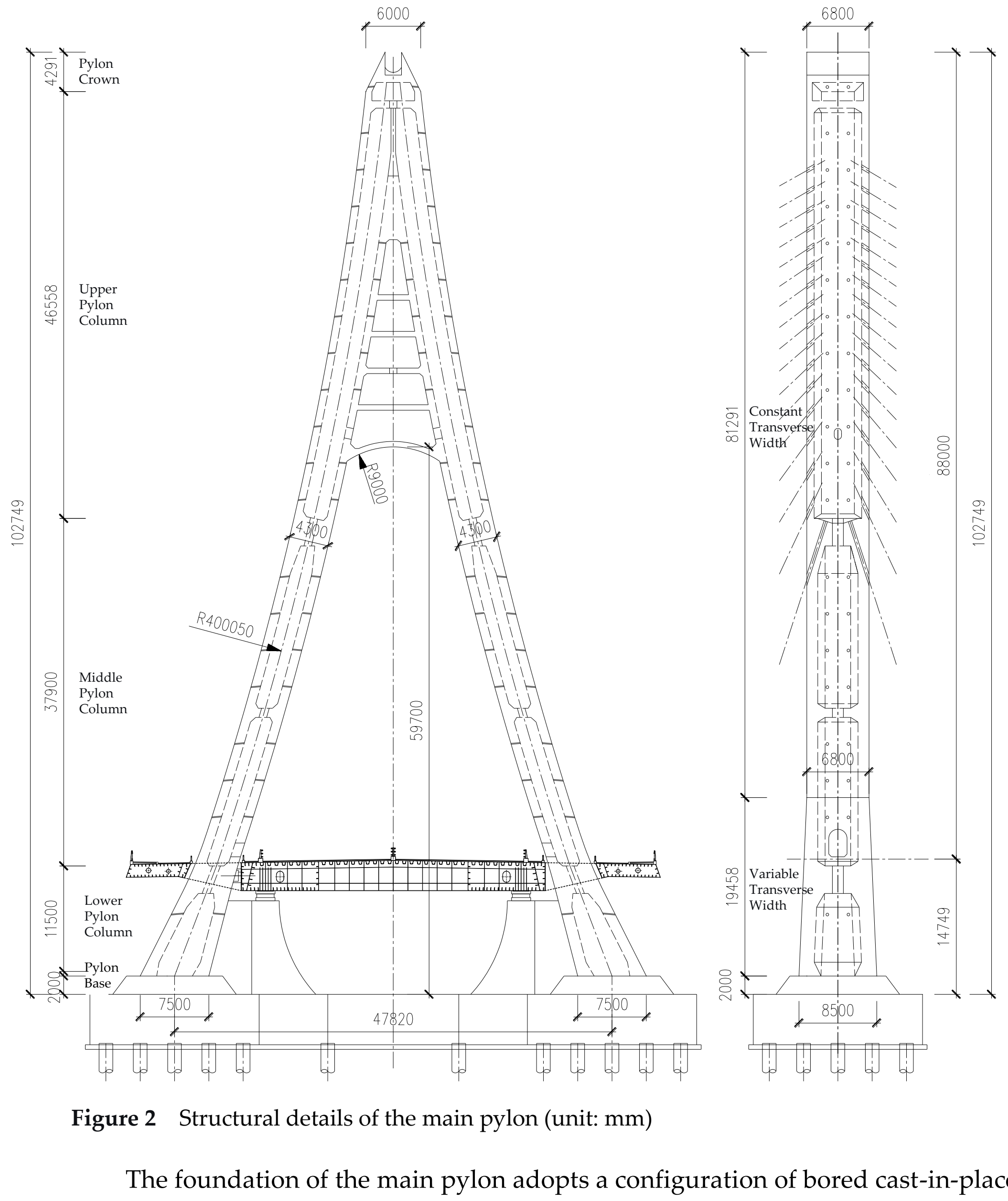


Figure 2 Structural details of the main pylon (unit: mm)

The foundation of the main pylon adopts a configuration of bored cast-in-place piles combined with a dumbbell-shaped pile cap. The plane dimensions of the pile cap are 18.5 m in the longitudinal direction and 66.32 m in the transverse direction, with a thickness of 5.5 m. The width of the dumbbell-shaped necking region at the center of the pile cap is 11 m. Under each pylon leg, 25 bored cast-in-place piles with a diameter of φ1.5 m are arranged. In addition, four bored cast-in-place piles of the same diameter are symmetrically arranged at the transverse crossbeam location. The pile tips extend into the pebble layer. The pile cap is constructed with C40 concrete,

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with a 2.0 m thick C40 pylon base above it and a 0.5 m thick C25 sealing concrete layer below. Acting as a transverse crossbeam, the pile cap is equipped with 36 prestressed steel tendon bundles (Φ15.2–19), as shown in Figure 3.

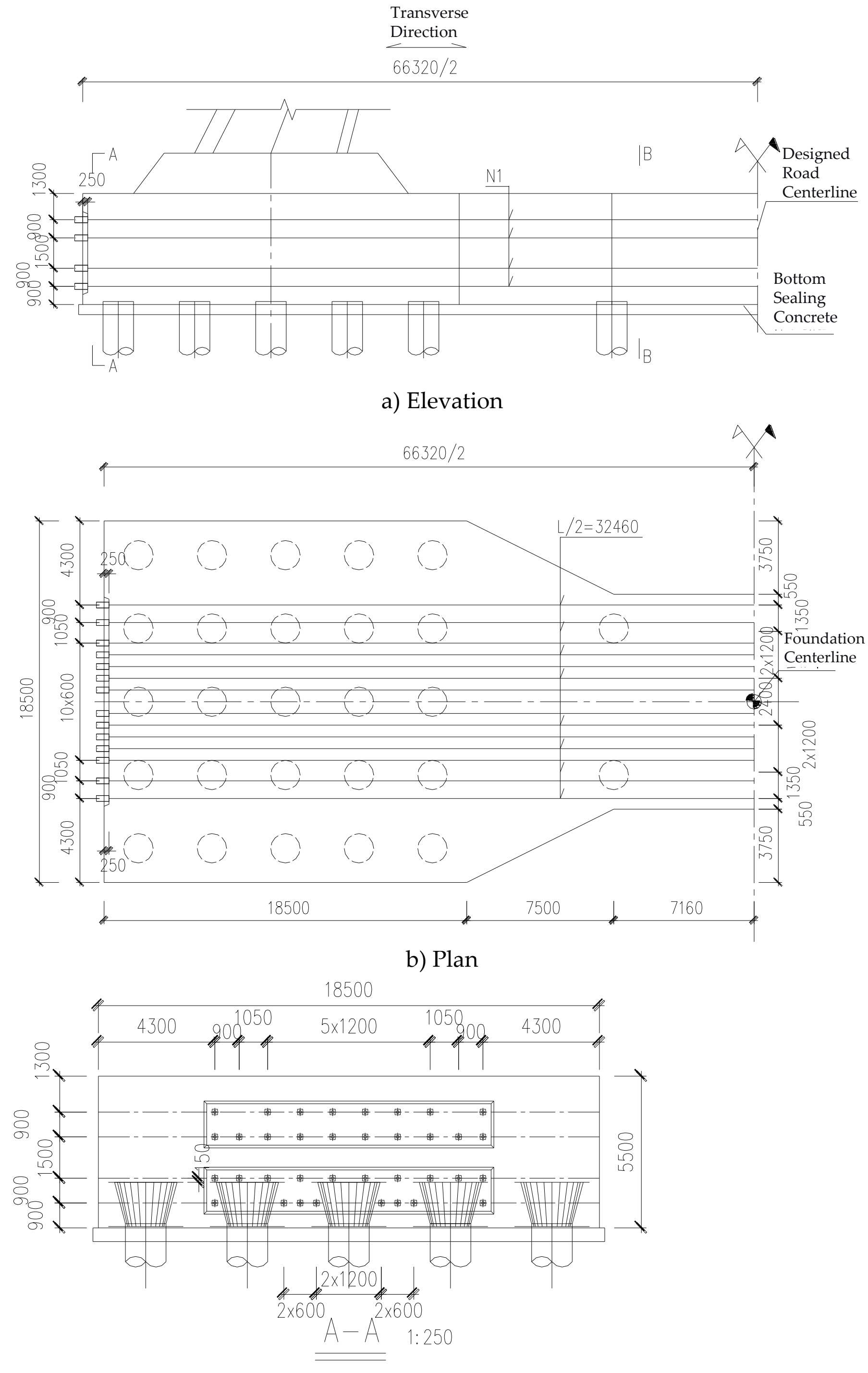


Figure 3 Layout of the prestressed tendons in the pile cap (unit: mm)

3 Full Bridge Finite Element Analysis

3.1 Full Bridge Grillage Model

The overall structural analysis was performed using the finite element analysis software MIDAS Civil, in which a full bridge spatial grillage model was developed, as shown in Figure 4. In this model, the main girder, main pylon, piers, pile cap, and pile foundations were simulated using beam elements, whereas the stay cables were modeled using tension-only truss elements. The cross-sectional dimensions were defined according to the actual geometry, and the variable width of the bridge deck was represented using equivalent stiffness. The pile foundations of this bridge are socketed piles. In the grillage model, the full pile length was modeled, with vertical supports applied at the pile bases. The horizontal restraint provided by the surrounding soil along the pile shafts was simulated by equivalently calculating the soil springs.

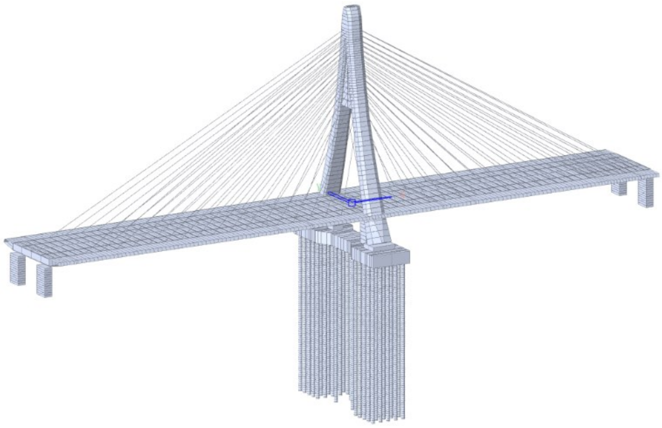


Figure 4 MIDAS civil spatial grillage calculation model

The loads considered in the global model include self-weight, vehicle load (Urban-A), pedestrian and nonmotorized vehicle load (in accordance with the "Code for Design of Urban Bridges" (2019 Edition)), wind load (design basic wind speed, V_{10} = 27.9 m/s), and settlement load (uneven transverse settlement of the main pylon). To investigate the mechanical behavior of the prestressed pile cap, the analysis focuses on load cases under frequent load combinations, as summarized in Table 1:

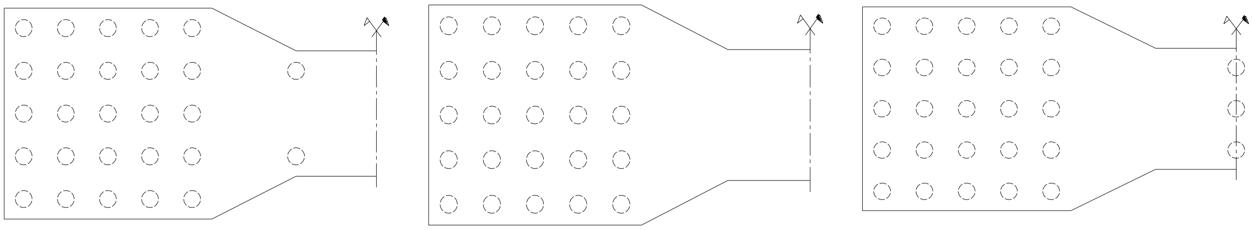
Table 1 Frequent load combinations

Load Case	Coefficient
Dead Load	1
Vehicle Load + Pedestrian Load	0.7 + 0.4
Temperature Load (Pylon, Girder)	0.8
Tendon Primary (CS)	1
Tendon Secondary (CS)	1
Uneven Settlement	1

3.2 Comparison and Selection of Three Schemes

Prestressing of the pile cap is applied in a single tensioning stage. The pile cap is subjected to multiple external forces from the pile foundations, the pylon, the prestressed tendons, and the pylon legs, resulting in complex stress conditions. The span of the pile cap is 33.32 m. Because of the large width of the main girder, the horizontal tensile force exerted by the A-shaped pylon on the pile cap is significant, and the overturning moment on the outer side of the pylon is substantial, further increasing the complexity of the stress state in the pile cap.

The span at the dumbbell-shaped necking region in the center of the pile cap is 28 m. It is necessary to control the bending moment in this region. An effective approach is to increase the number of piles, thereby reducing the span. Therefore, a comparative study on the number of piles arranged in this region is required. Three schemes are established in this paper. Scheme 1: Arrangement of 2+2 piles at the necking region; Scheme 2: Arrangement of 0 piles at the necking region; Scheme 3: Arrangement of 3 piles in the middle, as shown in Figure 5.



a) Scheme 1 b) Scheme 2 c) Scheme 3

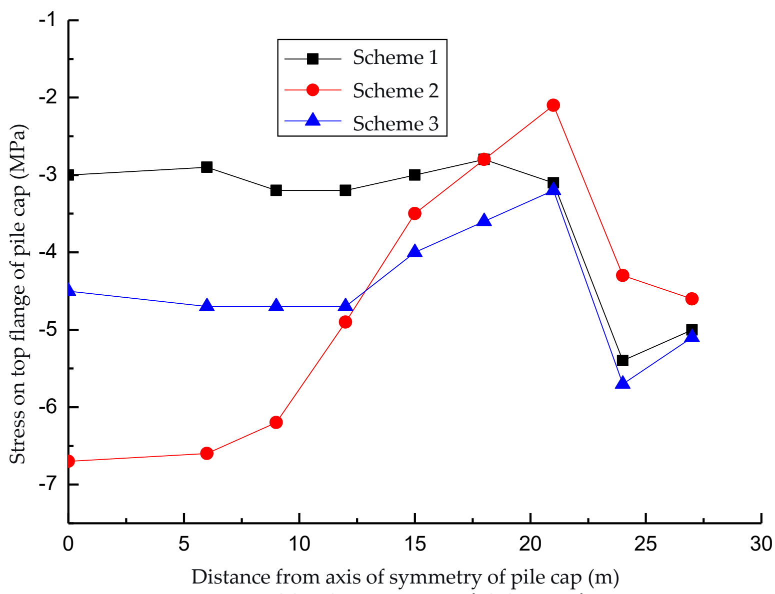
Figure 5 Layout of pile cap for three schemes

3.3 *Analysis of Scheme Results*

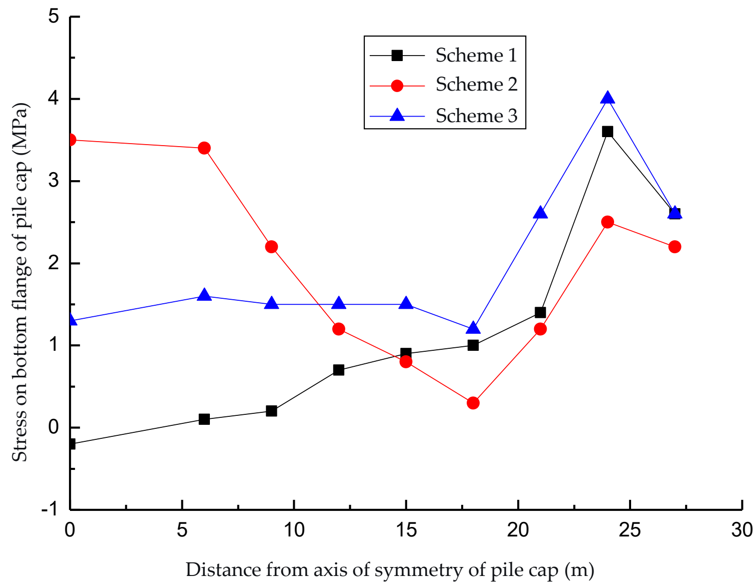
Three global models corresponding to Schemes 1-3 were established. The stresses on the top and bottom flanges of the pile cap under frequent load combinations, as well as the vertical deformation of the pile cap (excluding uneven transverse settlement of the main pier), were calculated, as shown in Figure 6.

As shown in Figure 6, for Scheme 1, the compressive stress on the top flange at the axis of symmetry of the pile cap is -3 MPa, whereas that on the bottom flange is -0.2 MPa. Near the pylon, the compressive stress on the top flange is -3.5 MPa, while the bottom flange exhibits a tensile stress of 1.0 MPa. For Scheme 2, the compressive stress on the top flange at the axis of symmetry of the pile cap is -6.7 MPa, and the tensile stress on the bottom flange is 3.5 MPa. Compared with Schemes 1 and 3, Scheme 2 shows a more uneven stress distribution and significantly higher tensile stress on the bottom flange. The stress distributions of Schemes 1 and 3 are relatively similar; however, Scheme 1 exhibits a more uniform stress distribution.

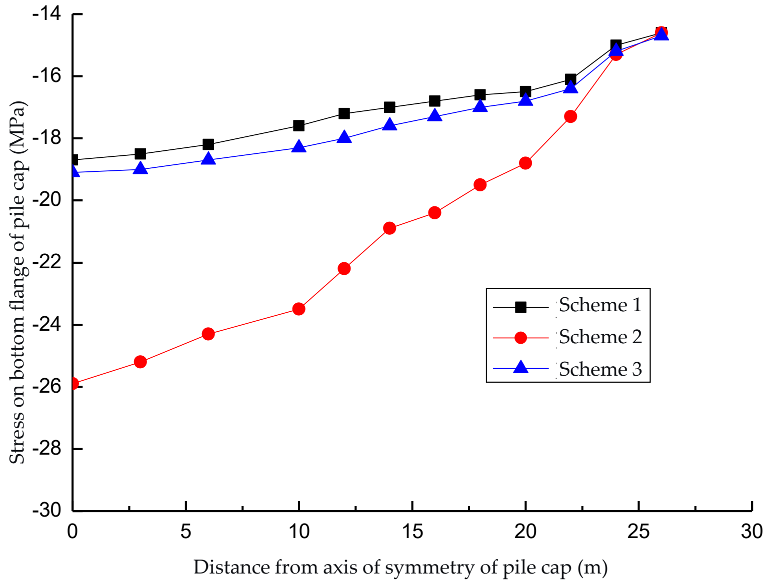
As shown in Figure 6c, Scheme 2 has a larger effective span, resulting in a maximum midspan deformation of 26 mm. By contrast, Schemes 1 and 3 exhibit smaller vertical deformations and more uniform deformation profiles, with maximum midspan deformations of -18.7 mm and -19.1 mm, respectively.



a) Stress on the top flange of the pile cap under frequent load combination



b) Stress on the bottom flange of the pile cap under frequent load combination



c) Vertical deformation of the pile cap under frequent load combinations (excluding settlement)

Figure 6 Calculation results of the three schemes

Based on the above analysis, Scheme 1 provides more favorable force distribution and deformation characteristics for the pile cap. However, a stress concentration is observed near the center of the pylon, where tensile stress on the bottom flange reaches approximately 3 MPa. These results are obtained from a grillage model. Because of limitations associated with beam-element modeling, boundary effects may be distorted and bending moments within the width of the pylon may not be accurately represented. Therefore, a dedicated analysis using a solid finite element model is required.

4 Solid Analysis of the Pile Cap

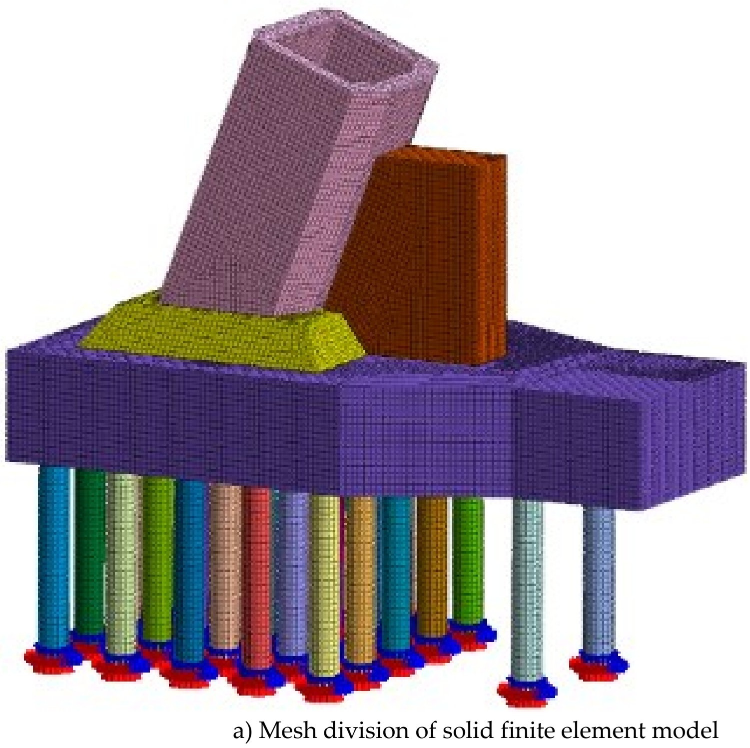
4.1 FEA NX Solid Model

A half model consisting of the pile cap, 10 m of the lower pylon column, the pylon legs, and 10 m of the pile foundation was constructed. The most unfavorable loading condition for the pile cap occurs when the overturning moment on the outer side of the pylon reaches its maximum. Therefore, the loads corresponding to the maximum bending moment at a location 10 m above the lower pylon column under the frequent load combination were extracted and applied in the FEA NX solid analysis.

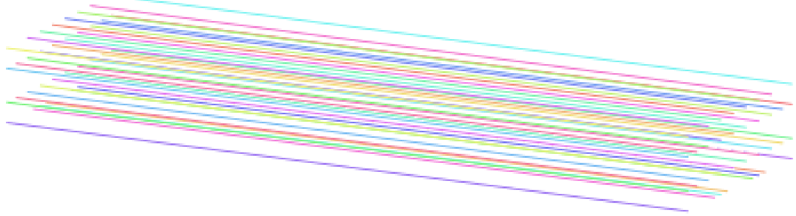
In the FEA NX model, the pylon, pylon legs, pylon base, pile cap, and pile foundations were simulated using three-dimensional solid elements, whereas the prestressed tendons were modeled as one-dimensional line elements, as shown in Figure 7.

Boundary Conditions: In the solid model, vertical and rotational constraints were applied at the bottom of the pile group. Because the main pier is located at the center of the river and the pile cap is exposed above the riverbed, the horizontal restraint provided by the silt at the pile tops is limited. Therefore, only 10 m of the pile length was modeled, and the skin friction was neglected. Symmetry boundary conditions were applied along the axis of symmetry of the pile cap.

Loads: The applied loads include self-weight, prestressing forces, internal forces under frequent load combinations on the transverse section of the main pylon, and support reactions at the piers under the same load combinations.



a) Mesh division of solid finite element model

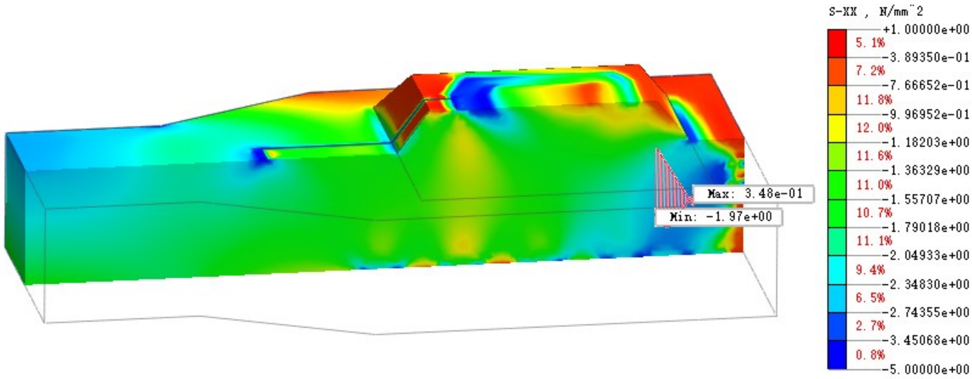


b) Tendon layout in the solid model

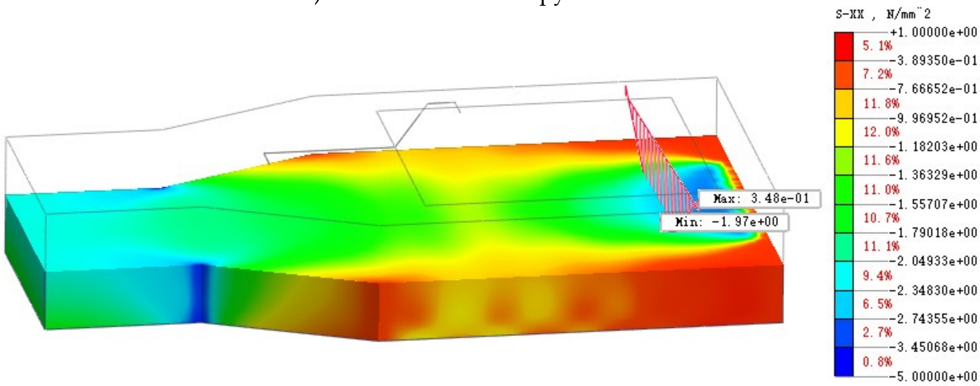
Figure 7 FEA NX solid model of the pile cap

4.2 Analysis of Results

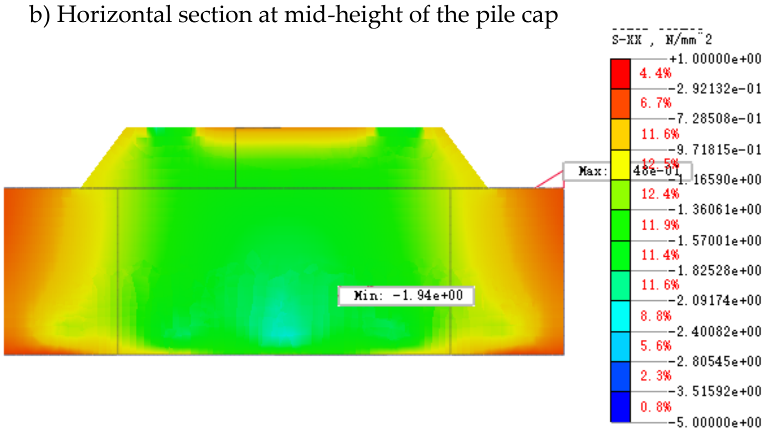
The local solid model of the pile cap was analyzed under frequent load combinations, and transverse stress contour plots for various sections were obtained, as shown in Figure 8. The first principal stress contour plot of the pile cap is presented in Figure 9.



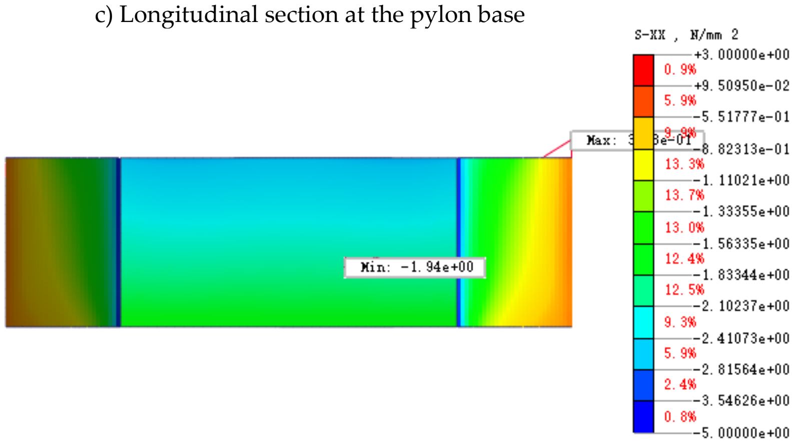
a) Cross section at the pylon location



b) Horizontal section at mid-height of the pile cap

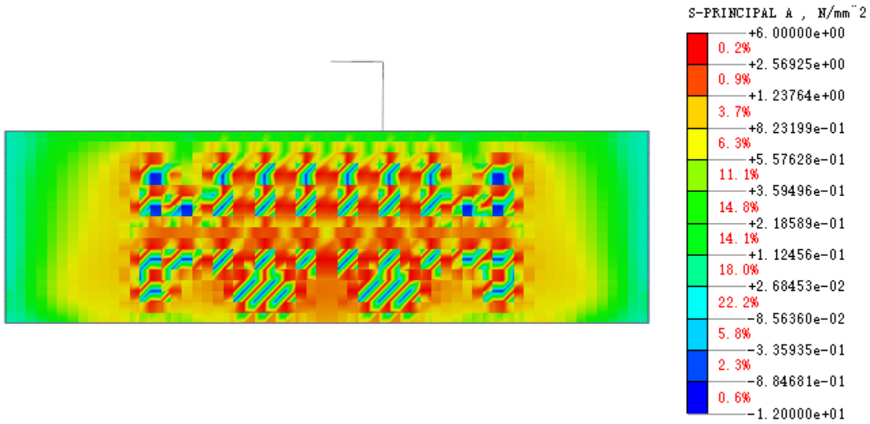


c) Longitudinal section at the pylon base

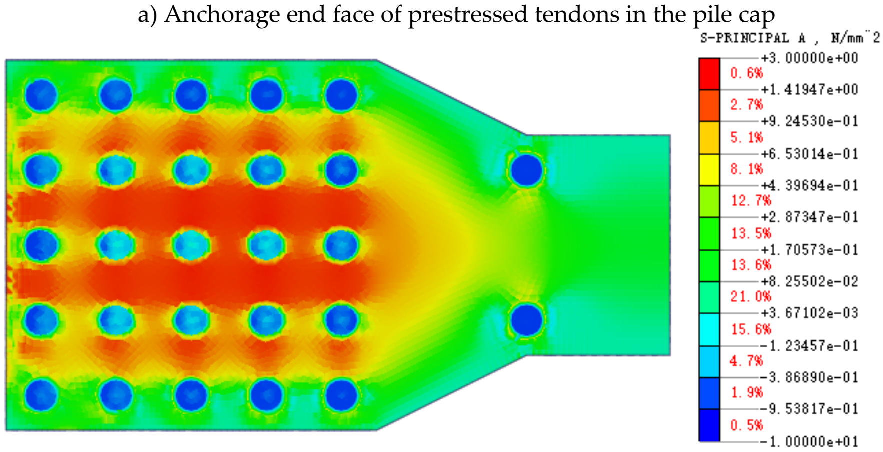


d) Longitudinal section at the axis of symmetry of the pile cap

Figure 8 Transverse stress contour plot of the pile cap (unit: MPa)



a) Anchorage end face of prestressed tendons in the pile cap



b) Tendon layout in the solid model

Figure 9 First principal stress contour plot of the pile cap (unit: MPa)

As shown in Figures 8a and 8d, the stress levels in the pile cap are generally within the range of 1 to 5 MPa. Transverse tensile stresses occur primarily at the edges of the pile cap, around the pylon base, and at the prestress anchorage zones. The compressive stress at the axis of symmetry is approximately -2.7 MPa on the top flange, and -1.7 MPa on the bottom flange. The analysis indicates that to balance the bending moment caused by the tension on the outer side of the pylon, the pile cap experiences a certain positive bending moment at its center of symmetry after the pile group bears part of the moment. Therefore, the design of the tendon layout must account for both axial force and bending moment effects induced by the pylon on the pile cap.

As shown in Figure 8b, stress transfer is primarily concentrated within the 11 m width of the necking region of the pile cap. Within this core region, the stress decreases from -2.34 MPa at the axis of symmetry to approximately -1 MPa near the center of the pylon leg base and then increases to about -5 MPa in the anchorage zone. This indicates that the confining force provided by the prestressed tendons is transmitted directly toward the center of the pile cap along a relatively short load path, with limited dispersion to the surrounding regions, demonstrating an effective prestressing action.

As shown in Figure 8c, the compressive stress at the pylon base exhibits an isosceles trapezoidal distribution, with stress values ranging from -1.16 to -2.09 MPa. This confirms that significant transverse compressive stress is present at the pylon base and that the transverse prestressing effect from the pile cap is effectively transferred to the pylon, providing adequate confinement.

As shown in Figure 9a, the principal compressive stress at the prestressed anchorage zones reaches approximately -12 MPa, while tensile stresses ranging from 1 to 6 MPa develop in regions outside the tendon ducts. Therefore, it is necessary to arrange longitudinal and transverse reinforcement meshes in the tendon anchorage zones during design. Figure 9b shows that the first principal stress near the center of the pile group at the bottom of the pile cap ranges from approximately 1.3 to 2.4 MPa. Accordingly, reinforcement meshes should also be arranged between the piles at the bottom of the pile cap.

To compare results, stresses at the center of the top and bottom flanges obtained from the grillage and solid models were evaluated. In the solid model, stress results were extracted at a location 0.3 m above the bottom flange to eliminate the influence of piles. The results are shown in Figure 10.

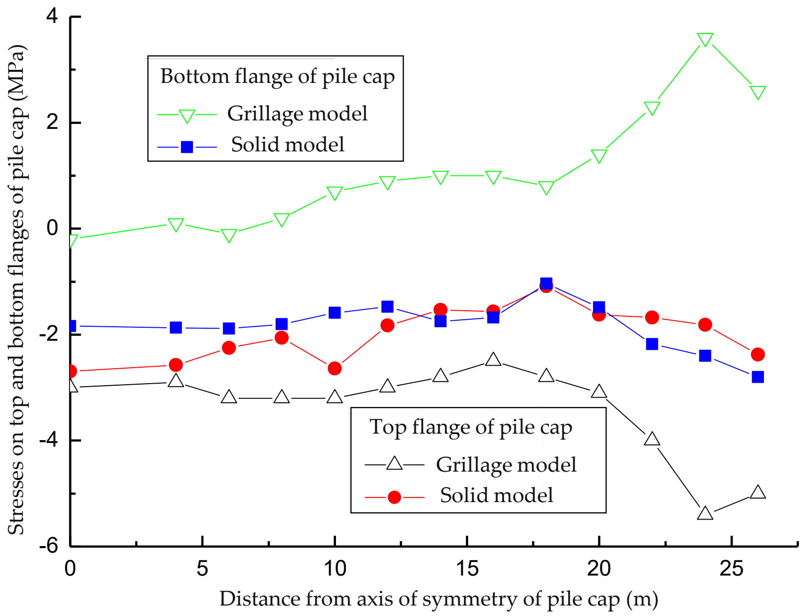
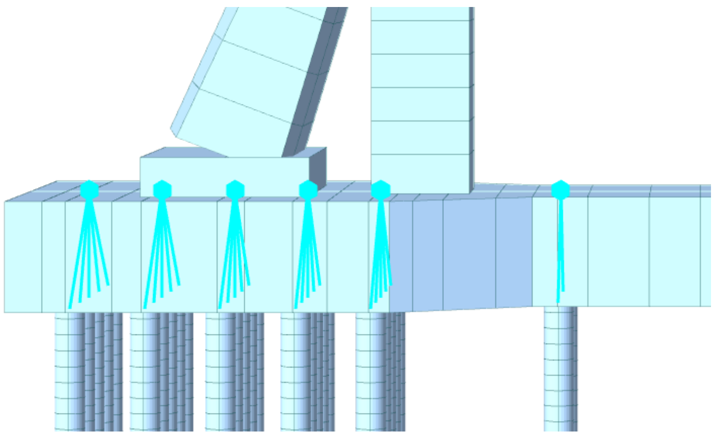


Figure 10 Transverse stress on the top and bottom flanges of the pile cap from the grillage and solid models

As shown in Figure 10, at the midspan along the axis of symmetry, the stress obtained from the solid model is approximately -2 MPa, whereas the corresponding stresses from the grillage model are -3 MPa (top flange) and -0.2 MPa (bottom flange). At the pylon location, the solid model yields compressive stresses of-2.1 MPa (top flange) and -2.6 MPa (bottom flange). By contrast, the grillage model produces stresses of -5.4 MPa and 3.6 MPa, respectively, indicating significant discrepancies. These differences arise from limitations of the grillage model.

In grillage model, the pile groups are not uniformly connected to a single node of the pile cap at the base of the pylon; instead, each row of piles is rigidly connected to nodes on the same plane of the pile cap, as shown in Figure 11.



a) Hidden Line View

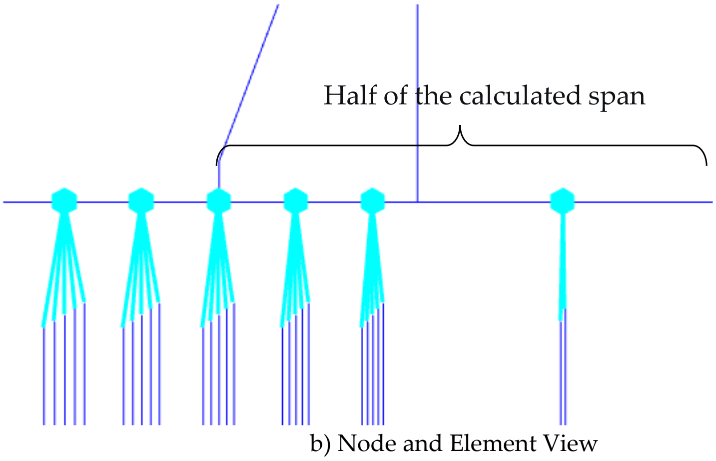


Figure 11 Schematic diagram of the boundary simulation for the pile cap in the grillage model

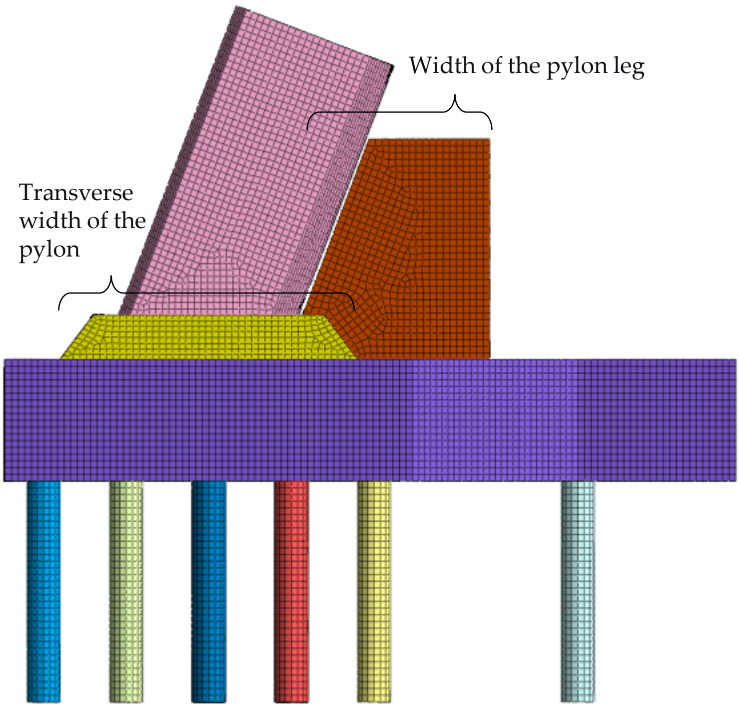


Figure 12 Schematic diagram of the boundary simulation for the pile cap in the grillage model

As a result, the connection between the pylon and the pile cap is represented as a beam-node connection, causing bending moments and axial forces to be concentrated at discrete nodes. This simplification neglects the influence of pile cap thickness and leads to stress concentration at the pylon location. Furthermore, because the pile cap has much larger cross-sectional dimensions than the pile foundations, stiffness-based force distribution causes most bending effects to be carried by elements directly connected to the pylon. Consequently, the grillage model overestimates bending moments at the axis of symmetry and underestimates the portion transferred to pile foundations.

The transverse width of the pylon (6.6 m), and the thickness of the pile cap (5.5 m) are of the same order of magnitude. According to Saint-Venant's Principle, the influence of member width cannot be neglected in this region. Therefore, the stress distribution near the pylon base is distorted. For accurate bridge design, recalculation using a three-dimensional solid finite element model is necessary.

5 Conclusions

This paper provides a detailed introduction to the design of the pedestrian and non-motorized vehicle crossing system for the Zhongxing Bridge. The structural response was analyzed by considering configuration characteristics, joint arrangements, and construction sequence. A comfort assessment was performed according to the German guideline EN03 (2007) for footbridge design. Finally, the design scheme for the key joints of the pedestrian staircase is explained. The main conclusions are as follows:

(1) Through comparative analysis, the symmetrical arrangement of "2+2" pile foundations in the dumbbell-shaped necking region (Scheme 1) is identified as the optimal configuration. This scheme effectively reduces the span of the pile cap, resulting in a more uniform stress distribution and smaller vertical deformation under frequent load combinations. Its mechanical performance is superior to configurations without piles or with a single row of piles in this region.

(2) The pile cap of an A-shaped pylon functions as a three-dimensional load-bearing system in which transverse prestressed tendons serve as key "balancing elements". By establishing a prestress field within the pile cap, particularly in the "dumbbell neck" region, the tendons directly resist the horizontal thrust from the pylon and partially replace the function of a crossbeam. This allows active prestressing to work in coordination with passive pile foundation support, enabling internal balance, spatial load redistribution, and efficient transfer of complex forces from the superstructure.

(3) To ensure structural safety, longitudinal and transverse reinforcement meshes should be arranged in the prestress anchorage zones and, in the regions between pile groups at the bottom of the pile cap. These measures help resist local tensile stress concentrations and control concrete cracking, providing practical guidance for the design of similar structures.

(4) Finally, for thick and large pile caps in A-shaped pylons without crossbeams, traditional spatial grillage models exhibit significant limitations. These models cannot accurately capture the complex stress transfer in the pylon-pile cap connection region and tend to overestimate local stress concentrations, leading to unreliable results. Therefore, verification and detailed analysis using three-dimensional solid finite element models are essential for accurate design.

Conflict of interest: The author disclosed no relevant relationships.

Data availability statement: The data that support the findings of this study are available from the corresponding author, Wu, upon reasonable request.

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