Research and Application of "Catwalk First, Saddles Later" Construction Technology for Long-Span Suspension Bridges in Mountainous Areas

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Abstract: Construction schedule management is a pivotal factor in engineering projects, where a well-structured timeline is decisive for ensuring the on-time completion and final acceptance of the project. In the construction process of suspension bridges, the installation of tower saddles typically employs a gantry lifting system. Conventional construction practices follow a sequential workflow where the main tower saddles are installed first, followed by the construction of the catwalks. However, the production cycle for suspension bridge saddles is relatively lengthy. Delays in saddle production or supply during the construction phase can directly impede the progress of subsequent critical processes, such as catwalk installation and main cable erection, thereby severely constraining the overall project timeline. To address this issue, this paper, drawing on a specific engineering case study, proposes an innovative construction technique aimed at providing more reliable technical support and practical insights for the construction of suspension bridges.

Keywords: Construction Period; Suspension Bridge; Catwalk; Cable Saddle; Gantry Mounting

1. Introduction

China, with its vast network of rivers, numerous gorges, and extensive mountain ranges, finds suspension bridges to be the most suitable type for spanning these complex terrains. Not only do they fully utilize the high-strength properties of materials, but they also boast significant advantages such as light weight, excellent ductility, and convenient construction, demonstrating unique applicability when traversing mountains, rivers, and valleys. During the construction of suspension bridges, the tower saddles are typically installed using a gantry lifting system. Traditional construction techniques follow a sequential operation mode where the main tower saddles are installed first, followed by the construction of the catwalks. However, due to the lengthy production cycle of suspension bridge saddles, any delays in production or supply can hinder the progress of subsequent critical processes such as catwalk and main cable installation, thereby significantly impacting the overall construction schedule of the project.

Taking the Huajiang Gorge Bridge as an example, this bridge is a steel truss suspension bridge with a total length of 2890 meters and a main span of 1420 meters. During its construction, design changes to the saddles led to production delays. If traditional suspension bridge construction procedures had been followed, the overall construction period of the bridge would have been delayed by nearly three months. To address this issue, the project innovatively adjusted the construction sequence, adopting a construction plan that involved erecting the catwalks first and then installing the saddles. This effectively resolved the mutual constraints between catwalk construction and saddle installation, ensuring the smooth progress of the project.

2. Design of Catwalks and Saddles

2.1 Design of Catwalks

The catwalk system of the Huajiang Gorge Bridge is arranged as shown in Figure 1. The system consists of two catwalks symmetrically positioned upstream and downstream along the bridge centerline, adopting a three-span continuous structure [1-2], with span combinations of 234.67 m + 1420 m + 485.18 m. The initial alignment of the three spans is based on the empty cable alignment, with sags of 3.75 m, 128.25 m, and 16.35 m, respectively. A total of nine transverse walkways are installed across the bridge, with one placed every 177.5 m in the mid-span and one each in the side spans on both banks. Along the longitudinal direction of the bridge, catwalk portals are installed at 50-meter intervals, supported by two steel wire ropes with a diameter of 60 mm. The side-span catwalk on the Liuzhi bank is anchored to the tunnel anchorage legs, while the catwalk on the Anlong bank is anchored to the front legs of the gravity anchorage. The anchorage system comprises embedded steel members, anchorage beams, and tie-rod systems. The embedded steel members are fabricated from Q345 steel, and their welding quality must comply with the current national standard Code for Welding of Steel Structures [3].

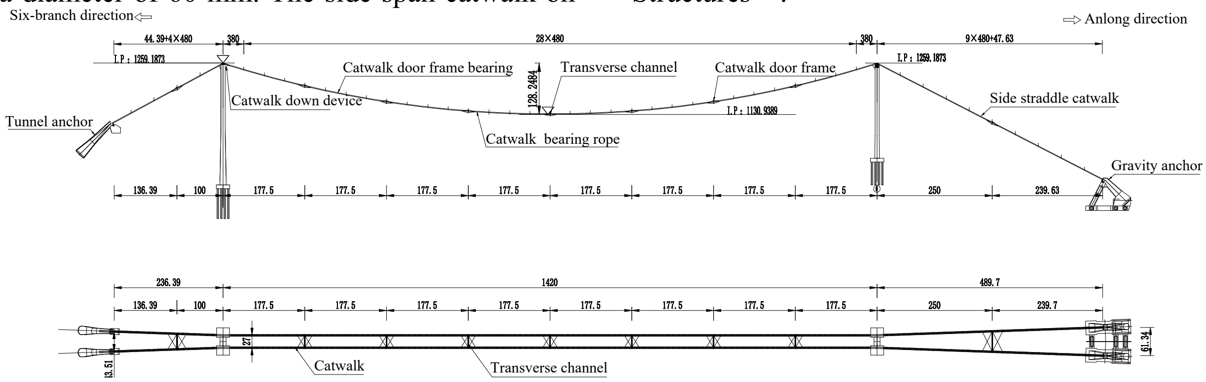


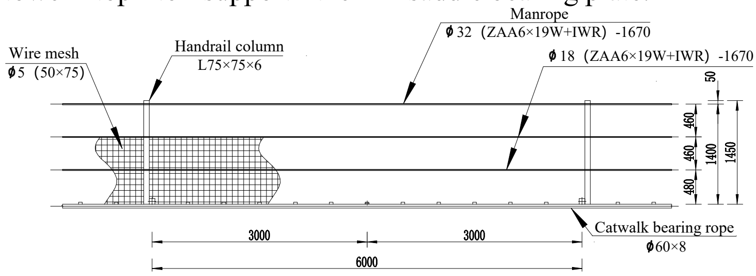
Figure 1. Layout of the Catwalk System (unit: mm)

The load-bearing cable system of the catwalk consists of eight steel wire ropes, each with a diameter of 60 mm, arranged at intervals of 12.5 meters. Along the longitudinal direction of the catwalk, a large crossbeam is installed every 12.5 meters and rigidly connected to the load-bearing cables using U-bolts to ensure structural integrity. Simultaneously, a small crossbeam is installed every 12.5 meters to connect the pedestrian walkways on both sides of the catwalk. To enhance structural stability, the large and small crossbeams are arranged in a staggered configuration. As shown in Figure 2(a), a handrail rope with a diameter of 32 mm is installed at the top of the guardrail, accompanied by two guardrail ropes with diameters of 18 mm, ensuring safe passage for construction personnel. The selection of all steel wire ropes strictly adheres to the safety factor requirements specified in the Specifications for Design of Highway Suspension Bridges (JTG/T D65-05-2015) [4]. Additionally, the catwalk deck is paved with a double-layer steel mesh, with mesh specifications of 50mm×70mm×5mm and 25mm×25 mm ×2mm, respectively. To further improve anti-slip performance, anti-slip wooden strips are tied to the mesh at intervals of 0.5 meters, with the specific arrangement illustrated in Figure 2(b).

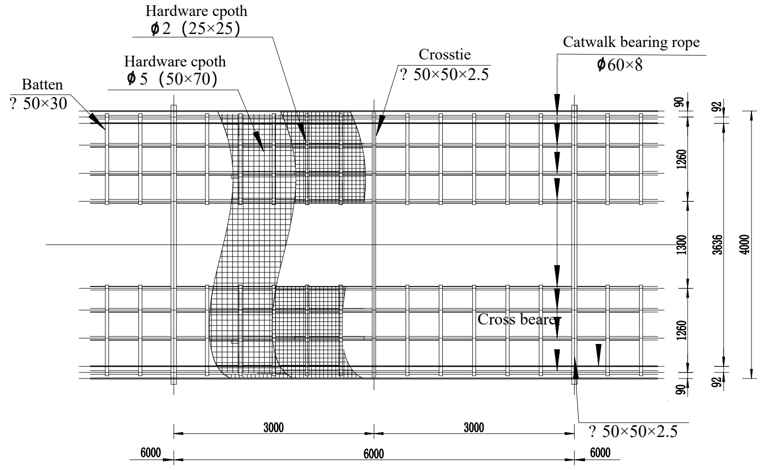
2.2 Saddle Design

2.2.1 Main Saddle

To facilitate fabrication, long-distance transportation, and on-site installation, the main cable saddles at the top of the main towers on both sides of the Huajiang Gorge Bridge adopt a three-piece saddle assembly, with the maximum lifting weight of a single unit being 41.3 tons. A single main cable saddle is divided into three saddle bodies of side span side, middle and middle span side, and is cast respectively, and the main cable saddle structure diagram is shown in Figure 3. The saddle structure combines forging and welding: the saddle groove at the base of the saddle head is forged from steel, complying with the technical requirements specified in Large Alloy Structural Steel Forgings (GB/T 33084-2016) [5]. The sidewalls of the saddle head and the saddle body are welded from Q420qE steel plates, with material properties meeting the standards of Structural Steel for Bridges (GB/T 714-2015) [6]. To accommodate relative displacements during construction, polytetrafluoroethylene (PTFE) sliding plates are installed at the base of the saddle. Additionally, vertical partitions are incorporated within the saddle groove to enhance the frictional resistance between the cable strands and the groove, as well as to facilitate strand positioning, thereby ensuring the stability of the strand configuration. Four additional backstay strands in the side span are anchored to the anchor beam of the tower-top saddle, with the groove partition spacing designed at 5 mm. A grid structure is also installed at the tower top to support the mounting and positioning of the main cable saddle bearing plate.

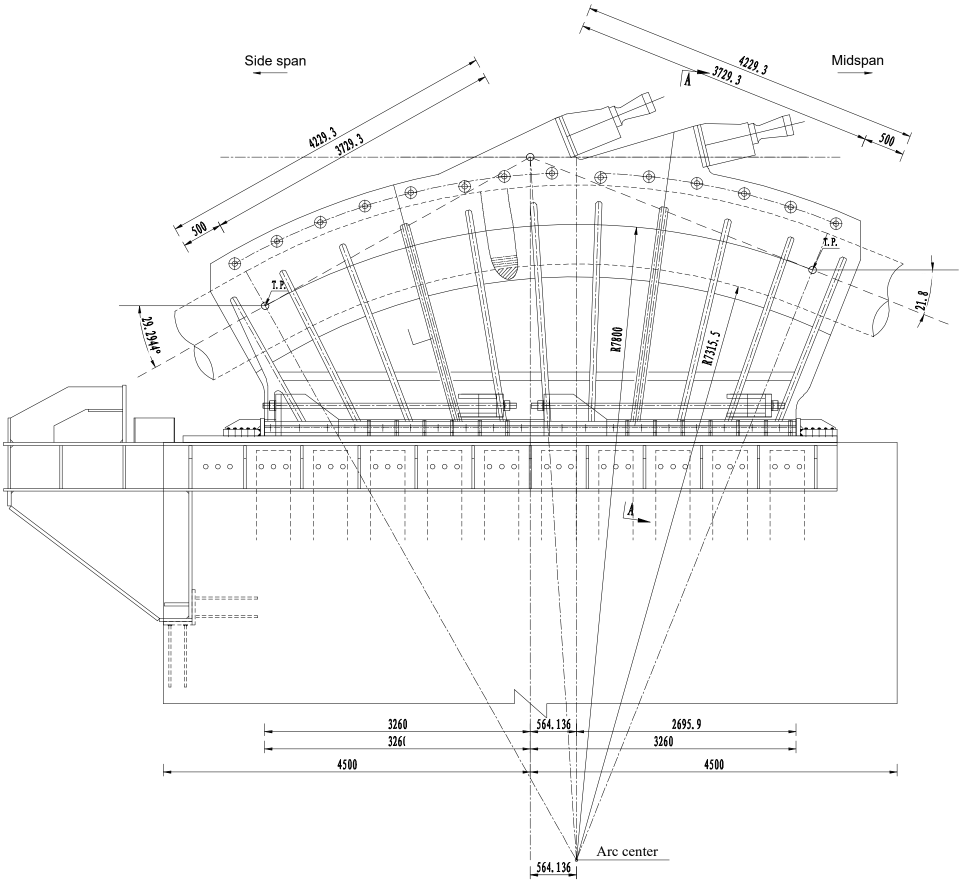


(a) elevation

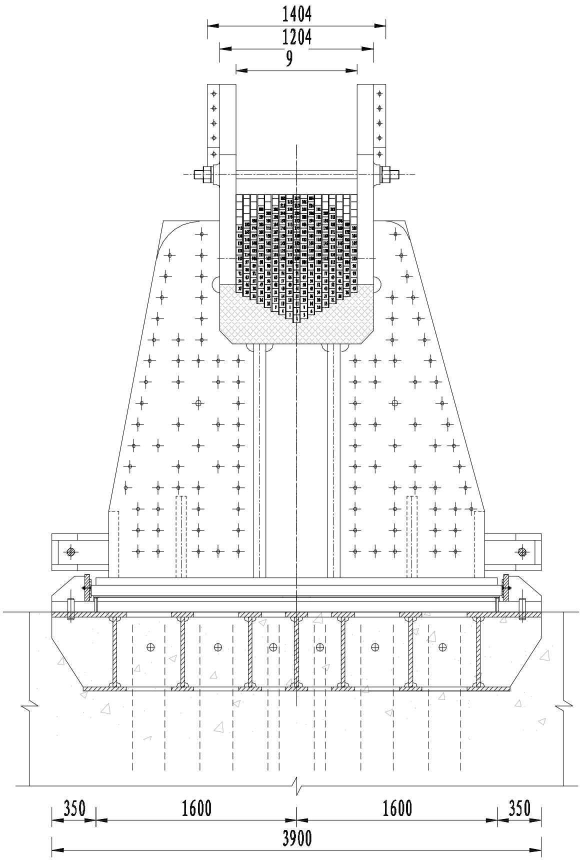


(b) plan

Figure 2. Structural Diagram of the Catwalk (unit: mm)



(a) elevation

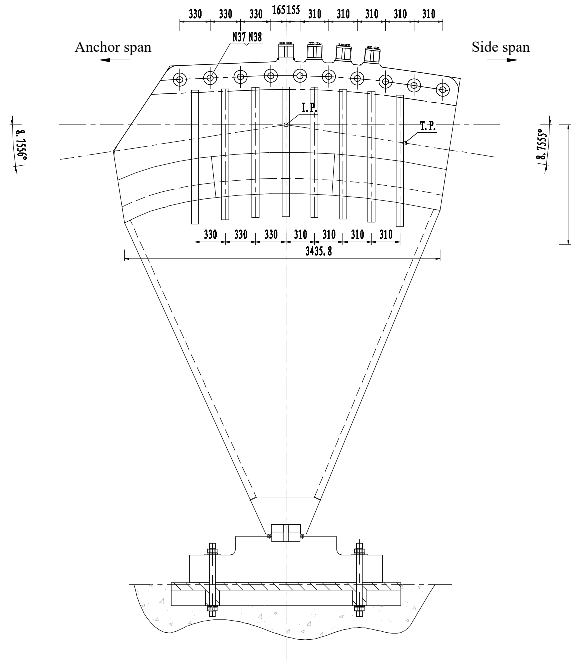


(b) A-A section diagram

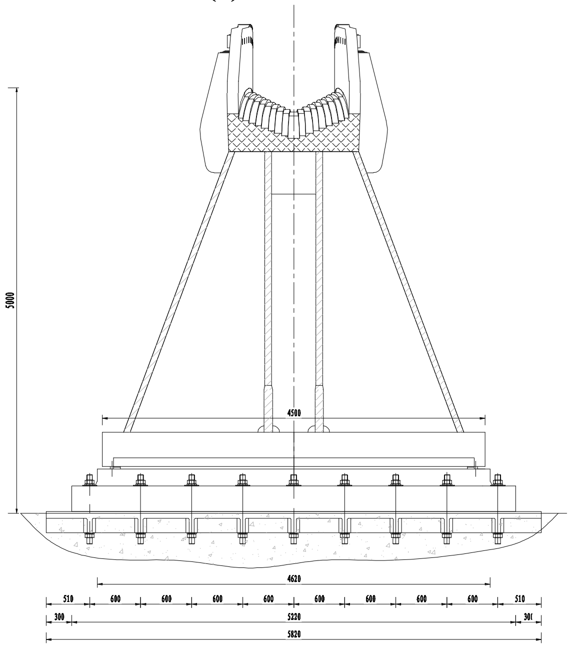
Figure 3. Structural Diagram of Main Cable Saddle (unit: mm)

2.2.2 Splay Saddle

The cable splay saddles of the bridge are fabricated as integral units, with one splay saddle body installed at each end of the main cable anchorage positions. A total of four splay saddles are provided for the entire bridge, with the maximum lifting weight of a single unit being 70 tons. The bottom of the loose cable saddle is provided with a hot-cast bottom plate as an embedded part for installation anchoring, and the bottom plate structure adopts the vertical stiffener form of roof and vertical and horizontal bridge arrangement, and its material properties are consistent with the main cable saddle, and the structure diagram of the loose cable saddle is shown in Figure 4. The theoretical distance from the cable splay point to the concrete surface at the base of the splay saddle is 5.0 meters. The horizontal curvature radius of the saddle groove sidewall on the Liuzhi bank is 20.0 meters, while that on the Anlong bank is 16.0 meters. Similar to the main cable saddle, vertical partitions are installed within the saddle groove to enhance the frictional resistance between the cable strands and the groove.



(a) Elevation



(b) Side view

Figure 4. Structural Diagram of Cable Saddle(unit: mm)

3. Construction Techniques

In conventional construction practices for suspension bridges, the sequence typically involves the installation of the main tower saddle followed by the construction of the catwalk. This study introduces an optimized design for the catwalk structure by adjusting the spacing between the mid-span deflection device of the catwalk and the main tower, thereby reserving vertical passage space for the saddle lifting process. Specifically, the catwalk compression device is installed after the completion of the saddle lifting, while the load-bearing cables of the catwalk are guided to both sides of the main tower saddle through deflection beams, consolidating the originally parallel-arranged cables. Based on the actual dimensions of the saddle and grid accessories, the required lifting passage space was determined, and the relative positioning between the catwalk deflection beams and the main tower was adjusted accordingly. This design proactively addresses the passage requirements for saddle lifting. Compared to traditional methods, this project innovatively reverses the construction sequence, adopting a process where the catwalk is erected first, followed by the installation of the saddle. The detailed construction workflow is illustrated in Figure 5.

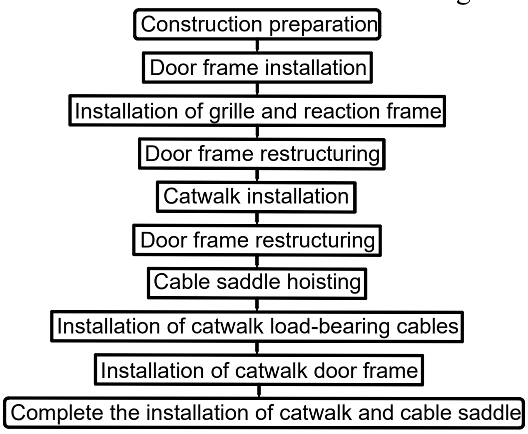


Figure 5. Construction Process Flow

4. Operation Points

4.1 Portal construction

The design of the portal frame structure is based on the structural configuration of the main tower and the lifting performance requirements. The main vertical members at the four corners of the tower-top portal frame are fabricated using HW400×400×13×21 wide-flange I-beams to ensure load-bearing capacity and stability. The main longitudinal beams at the top of the portal frame and the transverse beams at both ends are constructed as box sections welded from 12 mm and 10 mm thick steel plates. This design not only enhances the overall rigidity of the structure but also improves its bending and torsional resistance. Additionally, the connecting members in the middle section of the portal frame are made from HW400×400×13×21 wide-flange I-beams and HN400×200×8×13 narrow-flange I-beams to meet the mechanical performance requirements of different sections. The detailed structural model of the portal frame is illustrated in Figure 6.

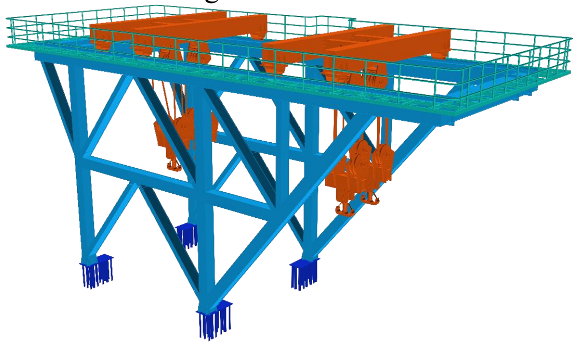


Figure 6. Overall Model of the Gantry

The installation of the tower-top portal frame is a critical prerequisite for the lifting of the cable saddle. After the tower-top concrete reaches its design strength, the main cable saddle portal frame is lifted and installed in sections using a tower crane. The specific construction sequence for the portal frame installation is as follows: first, the vertical columns are installed; once the columns are in place, the diagonal bracing between the columns, the top horizontal load-bearing longitudinal beams, the transverse connecting beams, and the cantilevered diagonal bracing are installed sequentially. During the installation process, the vertical alignment deviation of the portal frame columns must be strictly controlled. The longitudinal deviation must not exceed 2 mm, and the transverse deviation must not exceed 5 mm. Additionally, the levelness deviation of the main load-bearing longitudinal beams must meet the following requirements: the deviation within every 2-meter length should not exceed 1 mm, and the cumulative deviation over the entire 20.6-meter length should not exceed 9 mm. These precision requirements must be rigorously adhered to during construction to ensure the stability and safety of the portal frame structure.

4.2 Construction of Saddle Grillage and Reaction Frame

Before the final concrete pouring of the main tower top, the installation position for the saddle base plate must be pre-reserved in the tower-top portal frame. During the lifting process, two winch systems configured on the tower-top portal frame are used to hoist the base plate to the design elevation. Subsequently, the lifting beam is transversely moved using chain hoists to precisely position the saddle base plate above the reserved slot. After lowering the base plate, its levelness, elevation, and planar position are determined through precise measurement. Four 10-ton chain hoists are then employed to fine-tune the base plate, ensuring its installation position fully aligns with the design requirements. Finally, the concrete in the reserved slot for the base plate is poured to complete its fixed installation.

4.3 Catwalk Construction

Considering the topographic characteristics of the Huajiang Gorge Bridge and the practical conditions of the project, the mid-span load-bearing cables of the catwalk are installed using the bracket method, while the side-span load-bearing cables are installed using the tower crane traction method. The construction of the catwalk deck is uniformly carried out by sliding down from the tower top. The selection of these construction methods takes full account of factors such as terrain conditions, construction efficiency, and safety, ensuring the smooth progress of the catwalk construction. The detailed construction process of the catwalk is illustrated in Figure 7.

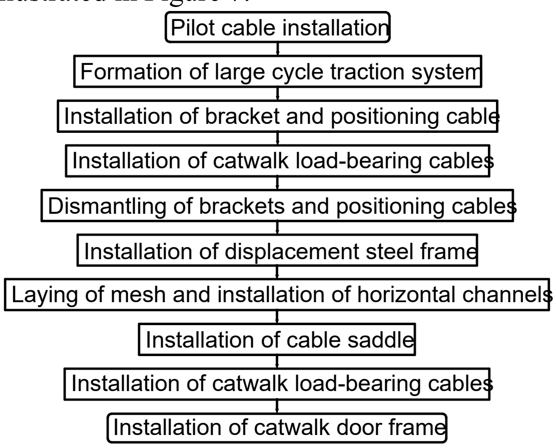


Figure 7. Process flow of catwalk and traction system

4.3.1 Catwalk Erection Instructions

(1) Mid-Span Construction:

To prevent excessive sagging of the cables during the traction and erection process, the load-bearing cables and positioning ropes for the brackets are pre-installed, followed by the installation of the brackets. This measure effectively ensures the stability of the cables and the safety of the construction process.

(2) Symmetrical Erection of Catwalk Load-Bearing Cables:

The erection of the catwalk load-bearing cables adheres to the fundamental principle of symmetrical construction. To minimize the impact on the displacement of the main tower during construction, synchronous operations are maintained for both the mid-span and side spans, as well as the upstream and downstream sides. This ensures that the displacement and torsion of the tower top remain within the design limits. The erection process is divided into three segments: the mid-span, which uses the bracket method traction system, and the two side spans, which employ the direct lifting method.

(3) Installation of Catwalk Mesh Panels:

The installation of the catwalk mesh panels is accomplished using the tower-top winch system in coordination with traction cables. Specifically, the mesh panels are first assembled on the tower-top working platform and then slid along the load-bearing cables toward the mid-span and anchorage directions, achieving efficient and precise installation.

4.3.2 Pilot Cable Erection

The traction system is a critical component in the installation of the superstructure of long-span suspension bridges, and the erection of the catwalk traction system marks a significant phase transition in the construction process [7]. In the construction of the Huajiang Gorge Bridge, the erection of the pilot cable was carried out in consideration of the relocation of high-voltage power lines. A steel wire rope with a length of 1700 meters and a diameter of φ22 mm (6-36WS+FC) was pre-tensioned as the pilot cable and anchored in an open area approximately 50 meters from the bridge site. After the main tower was topped out, a large-tonnage tower crane was used to lift the pilot cable from the ground to the tower top. At the Anlong bank tower top, the pilot cable was extended using a φ32 mm steel wire rope. Finally, the "small rope to large rope" method was employed to successfully complete the erection of the catwalk load-bearing cable traction system [8].

4.3.3 Erection of Bracket Load-Bearing Cables

Before the catwalk construction, two steel wire ropes with a diameter of φ32 mm must be erected in the mid-span as bracket load-bearing cables and temporarily anchored to embedded components. The installation steps for the mid-span bracket load-bearing cables are as follows:

(1) Preparation and Connection:

The bracket load-bearing cables are connected to a φ16 mm steel wire rope with a length 1.5 to

2.0 times the height of the main tower. The connected rope is then coiled onto a 100 kN winch located on the side-span side at the base of the Anlong bank tower. Using a tower crane, the cable end is lifted to the tower top and connected to the pulling device on the traction cable.

(2) Traction Process:

The traction system is activated, and the 100 kN winch at the base of the Anlong bank tower begins to release the cable. The bracket load-bearing cables are tractioned from the Anlong bank to the Liuzhi bank. During the traction process, to effectively control the sag of the load-bearing cables, the bracket load-bearing cables are suspended from the traction cable, with lifting devices installed at 50-meter intervals. Simultaneously, the winch applies appropriate counterforce to ensure the stability of the traction process.

(3) Anchoring and Adjustment:

Once the pulling device reaches the top of the Liuzhi bank tower, the cable end is anchored to the embedded components of the main tower. The traction cable is then retracted, and the lifting devices are removed from the operating platform at the top of the Anlong bank tower. Finally, the φ32 mm bracket load-bearing cables are adjusted to the design sag using the winch at the top of the Anlong bank tower, and the cable end is anchored to the Anlong bank tower.

4.3.4 Erection of Catwalk Load-Bearing Cables

The catwalk load-bearing cables for the side spans on the Liuzhi bank and the Anlong bank are erected using the direct lifting method, while the mid-span catwalk load-bearing cables are installed using the bracket method. The specific steps for erecting the mid-span catwalk load-bearing cables are as follows:

(1) Preparation and Initial Lifting:

After the completion of the bracket load-bearing cables and bracket construction, the erection of the mid-span catwalk load-bearing cables begins. First, the cable reel is placed on the cable release frame at the base of the Anlong bank tower. The cable end is then lifted to the tower top using a tower crane or tower-top winch and connected to the pulling device of the traction system.

(2) Traction Process:

The catwalk load-bearing cables are tractioned from the Anlong bank to the Liuzhi bank tower. When the remaining cable length on the reel is insufficient for brake-controlled release, the cable end is connected to a steel wire rope from a 50 kN winch located on the side-span side at the base of the tower. The winch applies appropriate counterforce to continue tractioning the cable end to the vicinity of the tower top. Finally, on the tower-top operating platform, the mid-span catwalk load-bearing cables are connected to the corresponding side-span catwalk load-bearing cables using molten metal sleeve joints, forming a continuous load-bearing cable. The temporary anchorage of the side-span catwalk load-bearing cables is then released.

(3) Final Adjustment and Anchoring:

The connected continuous catwalk load-bearing cables are lifted, transversely moved, and adjusted for alignment before being finally anchored, forming a complete three-span continuous catwalk load-bearing cable system. After completing the erection of one catwalk load-bearing cable, the same steps are repeated to erect the other catwalk load-bearing cable.

4.3.5 Installation of Deflection Frame

The deflection saddles for the catwalk load-bearing cables are symmetrically arranged on both sides of the main cable saddle at the tower top. To achieve precise adjustment of the load-bearing cable positions, a deflection steel frame is used for positioning. The specific steps are as follows: First, the deflection frame is hoisted to the tower top. Then, based on the actual dimensions of the saddle and bearing plate, the installation position of the deflection frame is determined. Ensuring that the lifting space requirements are met and the catwalk design specifications are adhered to, the deflection frame is installed and fixed to guarantee accurate positioning of the load-bearing cables and structural stability.

4.3.6 Installation of Catwalk Deck

After the adjustment of the catwalk load-bearing cables is completed, the installation of the catwalk deck begins. The catwalk deck mesh and transverse walkways are installed using the sliding method [9]. The specific construction steps are as follows:

(1) Support Structure Installation:

An H200×200×10 steel section is installed on the mid-span side of each main tower and connected to the wire rope head of the tower-top winch to serve as the support structure for the sliding system.

(2) Deck Mesh and Anti-Slip Strips Installation:

The catwalk deck mesh is laid, anti-slip wooden strips are tied, and the catwalk crossbeams are installed. During installation, the U-bolts connecting the crossbeams to the load-bearing cables should not be overtightened to ensure smooth sliding of the crossbeams.

(3) Balanced Installation of Side Spans:

To balance or reduce the horizontal forces on both sides of the tower columns during the installation of the catwalk deck and transverse walkways, the installation of the side-span catwalk deck and transverse walkways begins synchronously after a certain distance of mid-span installation, maintaining construction symmetry and stability.

(4) Continuous Installation and Final Adjustment:

After completing the installation of each deck section, the working platform is moved to that location to continue installing the next section, repeating the process until the catwalk is fully connected. When the catwalk deck slides to a gentle section and cannot slide further under its own weight, the traction system is used to pull the deck toward the mid-span, ensuring construction continuity and efficiency.

4.4 Saddle Construction

4.4.1 Preparations Before Saddle Lifting

Before lifting the saddle, the following preparatory work must be completed:

(1) Modification of the Portal Frame:

The connecting beams and guide wheel assemblies at the top of the portal frame used during the catwalk installation are dismantled. Subsequently, the crane rail and lifting trolley for the saddle are installed to meet the equipment requirements for saddle lifting.

(2) Installation of the Lifting Winch:

The winch wiring is arranged according to the design specifications, and the movable and fixed pulley assemblies are installed to ensure the stability and reliability of the lifting system.

(3) Removal of Obstructions:

The deck mesh and distribution beams between the main tower and the deflection steel frame on the mid-span side of the catwalk are removed to reserve sufficient operational space for the lifting of the saddle and bearing plate.

(4) System Trial Operation:

A trial operation of the lifting system is conducted to comprehensively check its operational status, ensuring the safety and efficiency of the lifting process.

4.4.2 Saddle Hoisting

Upon the completion of the catwalk surface net installation, the gantry hoisting system is reinstated to facilitate the saddle hoisting construction from the mid-span side. The gantry hoisting system employs two synchronized winches to lift the saddle. Once the desired lifting height is achieved, the saddle is transversely moved to the position above the installation point, followed by precise lowering and positioning. The specific construction sequence is illustrated in Figure 8.

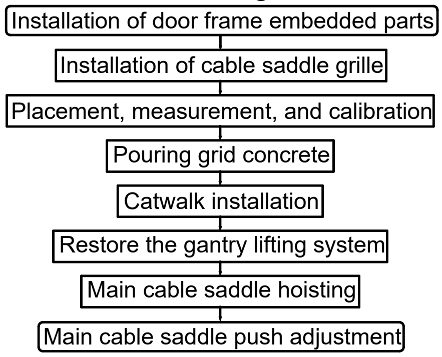


Figure 8. Installation Process of Cable Saddle.

4.4.3 Main Saddle Installation

The installation of the main saddle is carried out sequentially in the following order: the side-span saddle body, the intermediate saddle body, and the main-span saddle body. First, each saddle body is hoisted and positioned onto the upper bearing plate. After positioning, the three saddle bodies are connected and secured using high-strength bolts. Upon completion of hoisting, the main saddle is pre-deviated to its designed position and temporarily fixed. During the hoisting process, the saddle passes through the area between the main tower edge and the catwalk deflection frame on the mid-span side.

The main saddle is hoisted using the tower-top gantry lifting system. Prior to formal hoisting, a trial lift is conducted with a load of 1.05 times the maximum hoisting weight of the saddle body. The trial lift is performed in graded loading stages of 50%, 75%, and 105%. During formal hoisting, the saddle body is first lifted 20 cm above the ground and held stationary for 5 minutes to verify the balance of the center of gravity and the proper operation of the mechanical equipment. Once no abnormalities are confirmed, the main saddle gantry hoisting winch is activated to slowly lift the saddle body until it steadily clears the top surface of the bearing platform and ceases any vertical oscillations. The lifting speed is then gradually increased to the rated hoisting speed of the winch, ensuring a uniform hoisting process for the segmented saddle body. Throughout the lifting process, the bottom of the saddle body must remain essentially horizontal to avoid significant tilting.

When the saddle body is lifted to a position 1.5 m to 2.5 m below the tower top, the lifting speed is reduced. The lifting wire rope is locked once the bottom of the saddle body is 30 cm to 40 cm above the top surface of the tower grid. Subsequently, a chain hoist at the top of the gantry is used to pull the sliding crossbeam, moving the saddle body inward within the gantry. Once the saddle body reaches the installation position, longitudinal pull is stopped, and the chain hoist is locked. The hoisting winch is then activated to slowly lower the saddle body while workers use auxiliary tools such as hinges to precisely align the marked lines on the side of the saddle body with those on the upper bearing plate of the main saddle. Finally, the self-weight load of the saddle body is fully transferred to the upper bearing plate of the main saddle, completing the hoisting of the half-saddle body. The detailed process of the saddle hoisting is illustrated in Figure 9.

Figure 9. Hoisting of Cable Saddle Body

5. Conclusion

Through the optimized design of the catwalk structure, the spacing between the mid-span catwalk deflection device and the main tower was adjusted, providing vertical passage space for the saddle hoisting construction. Additionally, the construction sequence of the saddle and the catwalk was reorganized, eliminating the dependency of catwalk construction on saddle installation. Compared to traditional construction methods for similar ground-anchored suspension bridges, this optimized approach enables parallel construction of the catwalk erection and saddle installation. Alternatively, it allows for the catwalk to be constructed first, followed by saddle installation, effectively avoiding construction delays or schedule disruptions caused by delays in saddle production. This optimization not only significantly reduces construction time but also provides a reliable decision-making basis and technical reference for similar projects.

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