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Research on construction technology of "main cables installed ahead of stiffening girder" of self-anchored suspension bridge

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Abstract: *Self-anchored suspension bridge, as a unique structure, beautiful shape and adaptable bridge type, has been widely used in urban and complex terrain bridge construction. In order to improve the overall stability of the bridge, it is proposed to study the construction technology of self-anchored suspension bridge "main cables installed ahead of stiffening girder". Taking a self-anchored suspension bridge construction project in the center of an urban area as an object, a temporary anchorage system is installed, including temporary anchorages and tension cables, to ensure the safety of lifting; inverted lifting, inverted lifting and floating crane technology are used for lifting and loading of large mid-span sections and standard girder segments, which is an innovative method to overcome the construction problems; the construction of the merging system is converted, the temporary anchorage and tension cable are gradually lifted, and the cable strength of the main cables and the suspension rods is fine-tuned, and the second-phase constant load and adjusted cable strength are applied. The second phase constant load was applied and the cable force was adjusted to the design value to ensure the overall performance and safety of the bridge. Finally, the monitoring points are designed to monitor the stress and strain in different areas. The results show that the stress values at the bottom and top of the tower are relatively stable, and the highest stress value is within 350MPa, which proves that the structural strength of the bridge after construction can meet the use requirements.*

Keywords: *self-anchored suspension bridge; construction technology; main girder lifting; temporary tie*

1. Introduction

As an important form of bridge structure, suspension bridge is widely used in bridge engineering construction for its good force performance, large spanning capacity, lightweight and beautiful, strong seismic capacity and other characteristics [1]. Especially when crossing large rivers, high mountain valleys, gulf ports and other transportation obstacles, suspension bridges are often used as the preferred bridge type. However, traditional ground-anchored suspension bridges are not suitable for construction in areas with poor geologic conditions because of the need to build huge anchor structures. In order to solve this problem, bridge engineers have proposed a self-anchored suspension bridge scheme, which eliminates the huge anchorages and anchors the main cables directly to the girder ends, which not only reduces the cost, but also makes it possible to build suspension bridges in places where anchorages are not suitable. In recent years, scholars at home and abroad have carried out extensive research on the construction method of self-anchored suspension bridge [2]. In terms of construction technology, the traditional "girder first and then cable" construction method has been widely used, but the method has problems such as long construction period and great influence on navigation. In order to overcome these problems, scholars have proposed a variety of improved construction methods, such as the "ground anchor to self-anchor" construction program of setting temporary anchor spindles and temporary cables, and the "cable before girder" construction method [3]. In the research of "cable before beam" construction method, scholars at home and abroad have made some progress. For example, Dongguan Dongjiang South Tributary Harbor Bridge adopts the construction method of "main cables installed ahead of stiffening girder", which successfully solves the problem of water navigation [4]. This bridge structure adopts the "inverted suspension" construction technology, which effectively copes with the challenges of the steep main cable slopes and the complex and changeable routes, and successfully implements the advanced construction process of tensioning the cables first and then hoisting the bridge. In addition, some scholars have also studied the force characteristics and construction control of the "main cables installed ahead of stiffening girder" construction method by means of finite element modeling and simulation analysis, which provides theoretical support for the application of this method. On the basis of summarizing the research results of the previous researchers, this paper further researches the key problems and implementation methods of the construction technology of self-anchored suspension bridge "main cables installed ahead of stiffening girder". By optimizing the construction steps and processes, the impact of construction on navigation is reduced, and the construction efficiency and quality are improved.

2. Project overview

Located in the center of a city, this project spans a wide urban river, aiming to ease the surrounding traffic pressure and enhance the city image, and at the same time, as a city landmark, it serves the dual functions of traffic and landscape. The bridge has a total length of 450 meters, with a main span of 280 meters. It adopts a two-way six-lane design, with a design speed of 60 km/h to meet the standard of urban expressway. The bridge adopts self-anchored suspension bridge structure, the main cable consists of high-strength parallel steel wire bundles with a diameter of 120 mm and a design tensile strength of 1860 MPa. The main tower is a reinforced concrete structure with a height of 120 m. A cable saddle is set up at the top of the tower to support and guide the main cable. The stiffening beam is in the form of a steel box girder, 36 meters wide and 3.5 meters high, spliced from several sections, with a total weight of about 3,000 tons.

The horizontal distance between the upstream and downstream main cable centers of the bridge is 24 m. The distance between the suspension points of adjacent sections is 12 m. The distance between the suspension points on both sides of the main tower and the center axis of the main tower is 16 m. There are 43 suspension points of the main cable on one side. The main bridge span arrangement is shown in Figure 1.

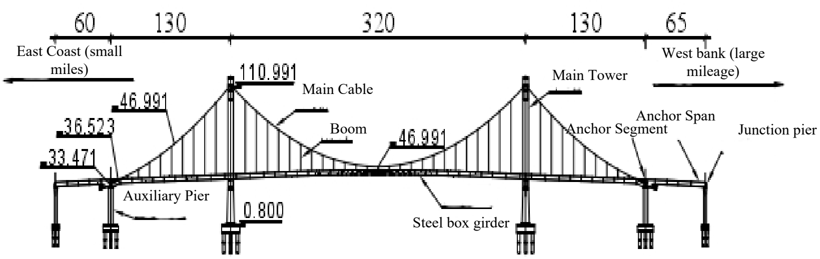

Figure1: Main bridge span arrangement

Sections of side and center span main girders are arranged symmetrically at the span centerline, and each lifting point corresponds to a section of main girder [4]. Sections with lifting points and slings are numbered, and the incremental direction of numbering is the same as the incremental direction of mileage, and the numbering is from 1 to 43 in order. Section F on the small mileage side is numbered as 1#F, section B on the mid-span is numbered as 22#B, and section F on the large mileage side is numbered as 43#F.

The main tower consists of two tower columns, two cross beams, all of which are hollow box section except for 3.0m at the root and 4.5m solid section at the top of the tower. The main material of the main tower is C50 concrete. The wall thickness of the tower column in the direction of the bridge and the direction of the transverse bridge is 0.8m, and it gradually thickens to 1.2m at the crossbeam and the tower base, and the crossbeam is hollow box section. The height of the upper and lower beams is 6.0m and the width is 5.0m. The main cable saddle adopts a fully cast steel structure, with oil grooves on the top surface of the base plate, which can be used to reduce the friction coefficient between the bottom surface of the saddle and the base plate by means of oil injection before the saddle is pushed up. Longitudinal guiding ribs are provided in the center of the top surface of the base plate to ensure the displacement of the saddle along the control direction. Vertical spacers are installed in the saddle groove [5]. After the cable strands are erected, the top is filled with zinc blocks, and then the sidewalls of the saddles are clamped by tie rods. The main tower saddle was set up with a reaction frame, and the saddle was jacked with the help of the reaction frame and jacks during the construction process. After each jacking to the specified displacement, the saddle is temporarily locked with tie rods

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and pitch locking plates. The timing and amount of jacking need to be determined according to the results of the construction phase analysis [6].

3. Construction Process

3.1 Installation of temporary anchoring system

The temporary anchorages consist of two sets of pier foundations and related reinforcement structures of the approach bridges, which need to be considered for their bearing capacity and stability during design. The foundation of each group of temporary anchorages adopts enlarged foundation or pile foundation to ensure that it can withstand the horizontal force transmitted by the main cable through the temporary cable during the lifting process [7]. According to the calculation, the design bearing capacity of each group of temporary anchorages should not be less than 1000 tons.

During installation, the foundation was first excavated and poured, and after the concrete reached the design strength, the construction of piers and reinforcement structures was carried out. The height of the pier columns of the temporary anchorages is designed to be 15 meters, with a cross-section size of 2 meters x 2 meters, using reinforced concrete structure [8]. The reinforcement structure includes transverse and longitudinal steel beams and supports to ensure the overall stability of the temporary anchorages.

The temporary cable is made of high-strength, low relaxation steel wire rope with a diameter of 50 mm and a design safety coefficient of not less than 3.5. The upper anchor point of the temporary cable is anchored to the temporary anchoring lugs at the extended position of the web of the G-beam section, and the lugs are made of Q345 steel plate with a thickness of 30 mm, and are connected to the G-beam section by welding.

During installation, the temporary cable is first lifted to the design position by crane, and then the hydraulic tensioning equipment is used to pre-tension the temporary cable to ensure that it is in a taut state. After the pre-tensioning is completed, the lower anchor point of the temporary cable is anchored at the designated position of the temporary anchor, and fine-tuning is carried out through the adjusting device to ensure that the tension of the cable meets the design requirements [9].

In order to prevent the anchor span girder segments from drifting during the lifting process, the auxiliary pier and G-beam need to be temporarily cemented. The temporary fixation adopts the connection device composed of steel plate and steel strand, the thickness of steel plate is 20 mm, the diameter of steel strand is 15.2 mm, and the design bearing capacity is not less than 500 tons.

During installation, steel plates are first installed at the connection position of the auxiliary pier and the G-beam, and then the two are connected together by means of steel strands and prestressing is applied. The magnitude of the prestressing force should be calculated according to the maximum horizontal component force that may occur during the lifting process, with sufficient safety margin [10].

3.2 Main girder lifting

Due to the limitation of construction conditions and other factors, the B girder section and 21#A1, 23#A1 girder sections in the midspan need to be formed into a whole large section and stiffened in advance, and lifted as a whole during hoisting. The total length of the mid-span section was about 34.8m, weighing about 637.6t.

Due to the small span of this bridge, the yag-span ratio is large, and the mid-span sling length is short, which makes the vertical distance between the main cable and the top surface of the main girder in the middle of the span when lifting is small, and the cable-carrying crane can't climb and set up the mid-span steel box girder on the main cable; at the same time, due to the restriction of the construction site, the floating crane can't carry out the hoisting of all the steel box girder, and the conventional lifting method can't satisfy the construction requirements [11].

In view of the above, the bridge innovatively adopts the lifting methods of inverted lifting process, positive inverted lifting process and floating crane process as follows.

(1) Inverted lifting process, mainly used for lifting mid-span large sections and most of the standard girder sections (A4~A17 girder sections). There are 3 groups of inverted lifting equipment in this

bridge, one group is equipped with 4 sets of inverted lifting cranes, total 12 sets of inverted lifting cranes. The construction process is as follows: one inverted hoist is equipped near each corner of the main girder, and corresponding temporary lifting points and temporary cable clamps are set on the main cable. The inverted hoisting equipment is connected to the main cable through the stranded wires and temporary cable clamps, and lifts up the girder section synchronously with the girder section to be lifted. After the girder section to be lifted is connected with the previous girder section, the inverted lifting crane is dismantled [12]. While dismantling the inverted lifting crane, the installation of the inverted lifting crane can also be carried out for the next girder section to be lifted, which can greatly improve the utilization rate of the flow of equipments and increase the efficiency of the construction, thus shortening the construction period.

(2) Positive inverted lifting combined process is mainly used for lifting E girder section of side span merging section. When the large section is lifted to a certain height, and there is enough space below, the cable-carrying crane (specially designed to adapt to the small vertical distance) is used to take over the large section from above, and at this time, the inverted lifting system is gradually unloaded, completing the conversion from inverted lifting to positive lifting. The design of the cable-carrying crane needs to consider the short sling length and the weight of the large section, and choose high-strength steel wire rope with a diameter of not less than 50mm, and the carrying capacity of the crane is at least 700 tons to ensure the safety margin. The whole lifting process needs to be equipped with a professional monitoring team, using high-definition cameras, displacement sensors, stress-strain monitoring and other equipment, real-time monitoring of large segments and the status of the lifting system [13].

3.3 Transition construction of joint system

After the girder section is lifted and the boom is tensioned, the temporary consolidation between the auxiliary pier and the girder section needs to be gradually released. The purpose of this step is to transition the girder section from a temporarily supported state to a state where it can be freely stressed. It is starting from one end of the bridge, gradually advancing to the other end, releasing one or more temporarily consolidated auxiliary piers each time [14]. During the process of temporary unconsolidation, displacement sensors and stress-strain monitoring equipment are used to monitor the displacement and force conditions of the girder segments in real time to ensure structural stability.

As the girder segments are stabilized under load, the temporary tension cables need to be gradually released and removed. The purpose of this step is to allow the main cable and the girder section to share the load of the bridge, use high - strength, low - relaxation steel wire ropes with a diameter of at least 40 mm as the key materials, start from the central position of the bridge frame, and gradually and orderly release the tension of the temporary cables evenly to both ends. The tension released each time should not be too large to avoid excessive impact on the structure. During the release of the temporary tensioning ropes, tension sensors and displacement sensors are used to achieve real - time and accurate monitoring of the tension of the tensioning ropes and the displacement of the beam segments.

After the system conversion is completed, the cable forces of the main cables and booms need to be fine-tuned to ensure the overall performance and safety of the bridge. During the release of the temporary tensioning ropes, tension sensors and displacement sensors are utilized to achieve real - time and accurate monitoring of the tension of the tensioning ropes and the displacement of the beam segments. According to the design requirements, the cable forces of the main cables and booms are adjusted to a predetermined value to ensure that the stress state of the bridge meets the design requirements. During the fine-tuning process, stress-strain monitoring equipment and displacement sensors are used to monitor the cable force and displacement of the main cable and boom in real time.

After the completion of the main structure of the bridge, it is necessary to apply phase II constant loads (e.g., bridge deck paving, railings, etc.) and make final adjustments to the cable force according to the actual situation in order to ensure the long-term serviceability of the bridge. The bridge deck paving is made of wear-resistant, non-slip asphalt mixture, and the railings are made of high-strength steel or stainless steel. Starting from one end of the bridge, the second-phase constant load is gradually applied to the other end. According to the application of the second-phase constant load, hydraulic tensioning equipment or electric tensioning equipment is used to make the final adjustment of the cable force of the main cable and the boom [15]. During the process of applying the second-phase constant load and adjusting the cable force, stress-strain monitoring equipment and displacement sensors are used to monitor the cable force and displacement of the main cables and booms in real time to ensure that the stress state of the bridge meets the design requirements.

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4. Construction Effect Analysis

4.1 Monitoring site design

In order to ensure the structural safety and long-term stability of self-anchored suspension bridges after the adoption of the "cables before girders" construction technology, it is necessary to set up comprehensive monitoring points to track the performance indicators of the bridges in real time during construction and operation.

As the main load-bearing structure of the bridge, the stress and displacement state of the tower directly reflects the overall stress situation of the bridge. In this regard, this paper selects the tower bottom, tower top and tower body variable cross-section as the construction points, the specific point layout parameters as shown in Table 1.

Table1: Parameters for point placement

Monitoring Point	Sensor Type	Installation Description	Set Range/Accuracy
Tower Base	Stress-Strain Sensor	At the four edges of the tower base, one on each side, ensuring full cross-sectional coverage	±1000MPa, accuracy 0.1%FS
	Displacement Sensor	On both sides of the tower base, perpendicular to the tower axis, measuring horizontal displacement	±50mm, accuracy 0.01mm
Tower Top	Stress-Strain Sensor	At the top of the tower, arranged along the anchorage direction of the main cable, measuring stress caused by main cable tension	±2000MPa, accuracy 0.1%FS
	Displacement Sensor	At the center and both sides of the tower top, measuring vertical and horizontal displacements	Vertical ±100mm, Horizontal ±50mm, accuracy 0.01mm
Tower Body at Variable Cross-Section	Stress-Strain Sensor	Above and below the variable cross-section, three on each side, arranged at key positions before and after the cross-sectional change	±1500MPa, accuracy 0.1%FS
	Displacement Sensor	On both sides of the variable cross-section, measuring the inclination angle of the tower body	N/A

In order to measure the stress - strain state of the tower body, high - precision and high - sensitivity resistance strain gauges or fiber Bragg grating sensors are selected and precisely pasted or embedded in the key cross - sectional parts of the tower body. The sensors should be arranged in such a way that they can fully cover the stressed areas of the tower while avoiding mutual interference. In order to accurately measure the displacement change of the tower body, a laser rangefinder or a wire - drawing displacement sensor is installed at the preset fixed position of the tower body. The arrangement of the displacement sensor should take into account the deformation pattern of the tower body and the measurement accuracy requirements to ensure that it can accurately reflect the displacement state of the tower body. According to the designed bearing capacity and mechanical characteristics of the tower body, set the specific range of stress - strain monitoring, the required precision level and the appropriate sampling frequency. During the monitoring process, the stress-strain data should be recorded in real time and processed and analyzed to assess the stress state of the tower body.

4.2 Analysis of monitoring results

The results of displacement as well as strain monitoring under different monitoring points are shown in Table 2.

From the monitoring data, it can be seen that the stress values at the two monitoring points at the bottom of the tower (tower bottom-1 and tower bottom-2) remained stable during the two monitoring sessions, and the variation was small. This shows that the bottom structure of the tower was subjected to uniform loads during the construction of "cable first and then beam", and the structural strength was sufficient, without obvious stress concentration or overload phenomenon. The change of strain value also reflects the stability of the tower bottom structure. In the two monitoring periods, the change of strain value is consistent with the change of stress value, which indicates that the bottom structure of the tower maintains good elasticity performance during the stressing process.

Table 2: Bridge Displacement and Strain Monitoring Results

Monitoring Time	Stress-Strain Monitoring Points (Resistive Strain Gauge/Fiber Bragg Grating Sensor)	Stress Value (MPa)	Strain Value (με)	Displacement Monitoring Points (Laser Rangefinder/Wire Displacement Sensor)	Vertical Displacement (mm)	Horizontal Displacement (mm)
2023-04-01 08:00	Tower Base-1	350	1750	Tower Base-D1	0.2	-0.1
	Tower Base-2	348	1740	Tower Top-D1	1.5	0.3
	Tower Top-1	180	900	Tower Top-D2	1.6	0.2
	Variable Section-1	420	2100	Variable Section-D1	0.4	-0.2
2023-04-01 16:00	Tower Base-1	352	1760	Tower Base-D1	0.3	-0.15
	Tower Base-2	350	1750	Tower Top-D1	1.7	0.35
	Tower Top-1	182	910	Tower Top-D2	1.8	0.25

5. Conclusion

Self-anchored suspension bridge as a kind of bridge form with both aesthetics and practicality, the optimization and innovation of its construction technology has become the key to promote the wide application of this type of bridge. In this paper, a comprehensive and in-depth research on the construction technology of self-anchored suspension bridge "main cables installed ahead of stiffening girder" has been carried out, aiming at exploring a more efficient, environmentally friendly and economically feasible construction plan to adapt to the complex and changeable construction environment and the increasing traffic demand.

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