Structural Analysis and Alignment Control for symmetrical Double-Cantilever Casting Concrete Cable-Stayed Bridge

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Abstract. The main bridge of Cao Lanh Bridge is a double-pylon and double-cable-plane PC cable-stayed bridge with a main span of 350 m. The main edge beams were cast in situ with form-traveler by the method of asymmetrical double-cantilever, that was, the concrete casting and cable tension of the main span were prior to the side span during the construction of the symmetrical segments on the two sides of the cantilever. In order to study the structural characteristics and variation trend of alignment, the finite element model of the whole bridge was established by the software MIDAS Civil, and the parameters of concrete elastic modulus, shrinkage strain and form-traveler stiffness were modified during construction stages. The alignments of pylons and edge beams were controlled based on the analysis results of stresses, displacements and cable forces of construction stages. The results show that the alignments of pylons and edge beams in completed stage meet the requirements of specification and design.

Keywords: Cable-stayed bridge; asymmetrical construction; prestressed concrete; cantilever casting; structural analysis; alignment control

1 Introduction

These guidelines, written After over four decades of continuous development, China has emerged as the global leader in constructing cable-stayed bridges. These remarkable structures, particularly the beam of prestressed concrete, have witnessed widespread application in small and medium-sized span cable-stayed bridges. The decision to utilize this construction method stems from its multitude of advantages, including cost-effectiveness, outstanding durability, high stiffness, exceptional stability, and efficient utilization of material properties[1-2].

In light of China's growing economic strength, advancements in cable-stayed bridge construction technology, and the research and development of large-scale construction machinery and equipment, the current procedures and technologies for constructing concrete cable-stayed bridges are primarily formulated by considering the structural

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and mechanical characteristics. The symmetrically balanced cast-in-cantilever method is a commonly used technique in constructing the main beams of concrete cable-stayed bridges[1,3-4]. This method involves casting the concrete segment, with a symmetrical, balanced formwork traveller on both sides of the pylon column along the bridge. The cables are tensioned symmetrically and simultaneously. The most commonly used formwork traveller in construction is the front fulcrum formwork traveller. It has a reasonable structure that allows for the full utilization of the cable[5]. Concrete cable-stayed bridges constructed with asymmetric cantilever construction generally adopt the single cantilever method, which involves casting the side span with support and the middle span with a formwork traveller[6-7]. In the construction of the asymmetric double cantilever, there is a specific sequence for constructing the main beam of the main span and the side span, as well as for hanging and tensioning the stay cable. In the construction of the symmetric beam section, the concrete castring and tensioning of the stay cable are done on one side before being done on the other side of the cantilever.

At present, the only cable-stayed bridge in China that features asymmetric double cantilever construction is the hybrid beam structure of an asymmetric balanced system with side span cantilever casting and middle span erection by protrusion[8]. Therefore, there is currently no fully constructed concrete cable-stayed bridge in China that follows this specific design. This paper discusses the construction practice of the Cao Lanh Cable-Stayed Bridge in Vietnam in order to study the structural characteristics and alignment variation trend of an asymmetric double cantilever concrete cable-stayed bridge.

2 Project overview

The Cao Lanh Cable-Stayed Bridge is a Central Mekong Delta Regional Connectivity Project (CMDCP) located in Cao Lanh City, Dong Thap Province, Socialist Republic of Vietnam. The total length of the bridge is 2,015.7m, of which the main bridge is a semi-floating prestressed concrete cable-stayed bridge with double pylons and double cable planes. The span composition of the main bridge is (150+350+150) m. The overall layout of the main bridge is shown in Figure 1.

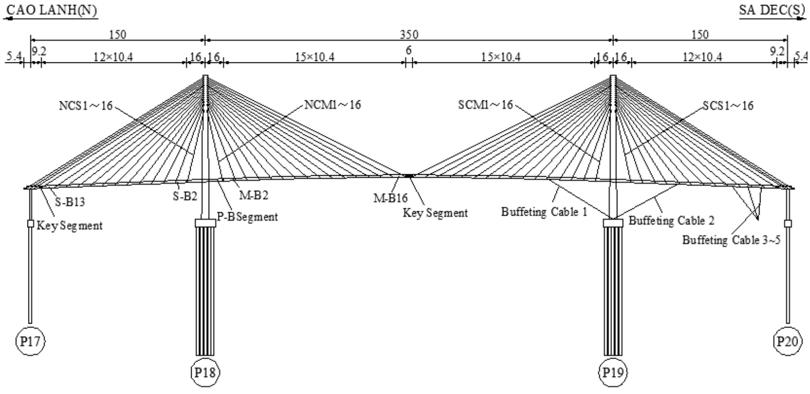

Fig. 1. General layout of main bridge of Cao Lanh Cable-Stayed Bridge(Unit: m)

The main span of the Cao Lanh Cable-Stayed Bridge has a bidirectional longitudinal slope of 4 %, and the grade change point is located in the center of the bridge. The main beam adopts a double-ribbed Π-shaped prestressed concrete section (Figure 2). It has a top surface width of 27.5 m and a bidirectional transverse slope of 2%. The bottom width of the side rib is 1.5 m, the section center height is 2.2 m, and the bridge panel thickness is 0.25 m. A prestressed beam, with a thickness of 0.4 m is installed every 5.2 m. The H-type pylon is 123.4 m high and has two beams. There are 16 pairs of parallel steel hinged cables on each side of the single pylon, and a total of 128 cables on the whole bridge. There is one pair of cross temporary cables in the 5# beam section of the middle and side span, as well as in the 10#-12# beam sections of the side span, and a total of 20 temporary cables in the whole bridge (Figure 1 only shows the half-span temporary cables, and the other half-span is arranged symmetrically). Two pairs of longitudinal supports, one pair of vertical supports, and one pair of horizontal wind-resistant supports are arranged on the lower beam of each pylon. The pylon foundation adopts a 24×Φ2.5 m drilled pile group foundation, and the side pier is connected to the main beam through U-shaped prestressed tendons.

The pylon is constructed using hydraulic climbing formwork and consists of a total of 33 sections. The length of the 0#-1# segments and the side span cast-in-place segments which are constructed by casting concrete on support are 32 m and 13.1 m. Segments 2#-13# on the side span and 2#-16# on the middle span are standard segments with the length of 10.4 m. They are constructed with asymmetric cantilever concrete method with formwork traveller. The length of the side span key segment (closure section) which is constructed by casting concrete on support is 1.5 m. The length of the middle span key segment (closure section) is 6 m, and the pouring construction is carried out using the hanging basket.

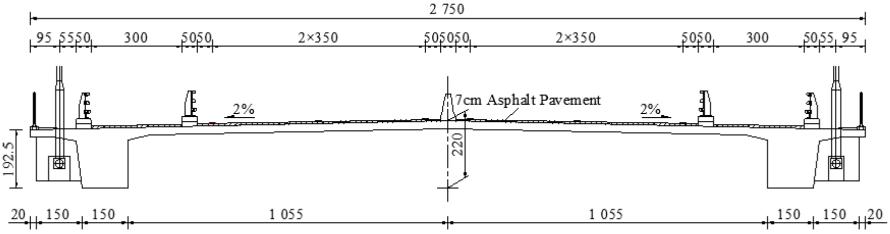

Fig. 2. Typical cross section(Unit: cm)

3 Structure analysis of main bridge

3.1 Structural characteristics

Design and construction characteristics.

The Cao Lanh Cable-Stayed Bridge is located in Vietnam. Affected by local economic and policy factors, it is difficult for foreign construction enterprises to import large-scale equipment and labor[9]. In order to address the limited construction capacity (mechanical equipment, technical expertise, etc.) of local enterprises and to reduce costs, the design and construction plan for asymmetric double cantilever concrete pouring is being implemented in the standard beam section of the bridge's main beam. The specific implementation steps for the standard beam section before and after side span closure are listed in Table 1 and Table 2.

Table 1. Construction steps of typical segment before closure of side span finished

Construction stage	Construction sequence
1	F/T-M movement, Anchor pod installation
2	F/T-S movement, Anchor pod installation, Form erection elevation adjustment
3	Middle cables 1st stressing
4	Bar construction of 1/2 segment
5	side cables 1st stressing
6	Bar construction of another 1/2 segment, Cross beam concrete of side span casting
7	Concrete of middle span and cross beam of middle span casting
8	Concrete of side span casting
9	Tendon of middle span stressing, Middle cables 2nd stressing
10	Tendon of side span stressing, Side cables 2nd stressing
11	F/T-M and F/T-S movement, Construction of next segment

Note: F/T-M indicates Formwork Traveller of middle span; F/T-S indicates Formwork Traveller of side span.

Compared to conventional double cantilever symmetrical concrete construction, the bridge has the following characteristics:

(1)The investment in construction equipment and personnel is lower, resulting in cost savings. However, the construction time is longer.

(2)The main beam suspension section has a length of 10.4 m and a significant weight of 4,590 kN. The front fulcrum formwork traveller has high stiffness and a large self-weight (2,650 kN). The length of the middle span closure section is long (6 m).

(3)The concrete for the main beam is poured in one continuous process, and the cable tension is not adjusted during the pouring process.

(4)When installing the cable, it is connected to the hanging basket through the prefabricated anchor block. Once the concrete is poured for the main beam, the anchor block and the beam body are integrated to form a single unit, sharing the load.

(5)The cable-stayed cables are installed, tensioned, and anchored one by one[10], and the entire bundle is not tensioned.

(6)Install 10 pairs of temporary cross cables, consisting of eight pairs for the side span and two pairs for the middle span. This will ensure the stability and safety of the structure when subjected to the most unfavorable unbalanced load and the maximum wind speed during construction.

Table 2. Construction steps of typical segment after closure of side span finished

Construction stage	Construction sequence
1	F/T-M movement, Anchor pod installation, Form erection elevation adjustment

3	Middle cables 1st stressing
4	Bar construction of middle span
5	side cables 1st stressing
7	Concrete of middle span and cross beam of middle span casting
9	Tendon of middle span stressing, Middle cables 2nd stressing
10	Side cables 2nd stressing
11	F/T-M movement, Construction of next segment

Note: F/T-M indicates Formwork Traveller of middle span; F/T-S indicates Formwork Traveller of side span.

Stress and response characteristics.

(1)During the construction of the asymmetric double cantilever, there is a significant unbalanced load at both ends of the main beam's cantilever. Affected by the change in cable force, the upper section and lower edge of the cable pylon experience significant stress variations during each construction step, particularly during the concrete pouring stage.

(2)The stress on the temporary cable, when placed in space, is complex and impacts the stress and deflection of the main beam.

(3)Under the unbalanced load, the deflection of the main beam and the horizontal displacement of the cable pylon change significantly.

3.2 Structural analysis

Finite element model.

Over the years, scholars at home and abroad have carried out a large number of theoretical

The three-dimensional model of the full bridge was established using the finite element software MIDAS Civil, as shown in Figure 3. Among them, the cable pylon, main beam, bridge pier, and pile foundation are simulated using spatial beam elements. The cap is simulated using spatial slab elements. The cable element, which is under tension only, is simulated using stayed cables and temporary wind resistance cables. The support is simulated using elastic connections. The spring boundary condition is used to model the pile-soil interaction. The front fulcrum hanging basket is simulated using virtual elements. The bridge has 2,757 nodes, 2,670 units, 232 rigid connections, 36 elastic connections, and 1,380 elastic supports. According to the construction scheme, 238 construction stages were divided for linear simulation analysis and calculation. The Ernst equivalent elastic modulus theory was used to modify the cable's elastic modulus, taking into account the influence of the cable's weight sag effect. The simulation of the construction stage took into account the time-varying effect of concrete. Additionally, the effects of shrinkage and creep of concrete were included in the simulation for a period of 10,000 days after the completion of the bridge.

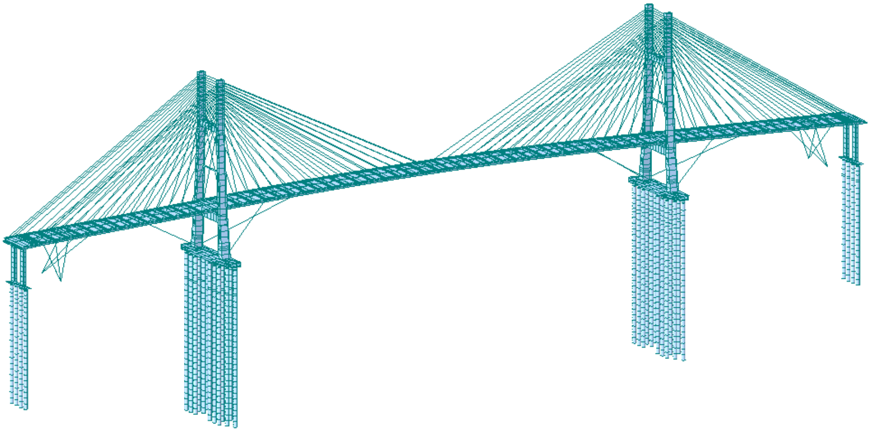

Fig. 3. Finite element model of structure

Modification of parameters.

(1) Elastic modulus of concrete

The main pylon, main beam, and pier of the Cao Lanh Cable-Stayed Bridge are made of C50 concrete (a special specification concrete label), and the design value of the elastic modulus is 38007 MPa. Standard specimen tests were conducted in the field laboratory to determine the actual elastic modulus of the on-site concrete. The calculation model took into account the curve of elastic modulus fitting based on the test data with age (Figure 4). The elastic modulus of concrete, measured after 28 days, is 40,380 MPa.

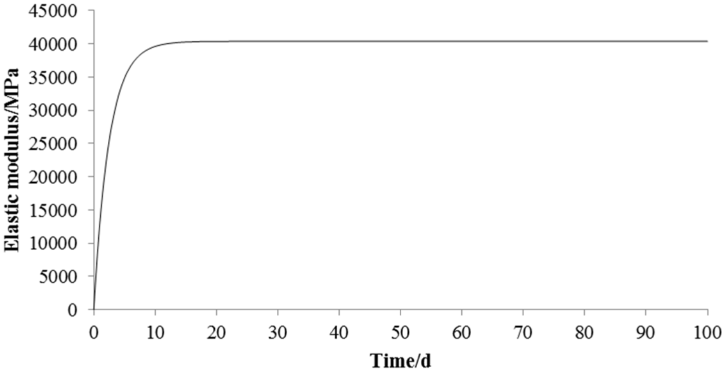

Fig. 4. Fitted curve of elastic modulus

(2) Concrete shrinkage strain

In order to accurately simulate the time-varying effect of concrete, a concrete shrinkage strain measuring system is installed at the bottom of the column. This system consists of a stress-free bucket and a vibrating wire strain gauge with temperature sensors, which are used to measure the shrinkage strain. After fitting the measured data, the shrinkage strain curve[11] was obtained (shortened to positive), as shown in Figure 5.

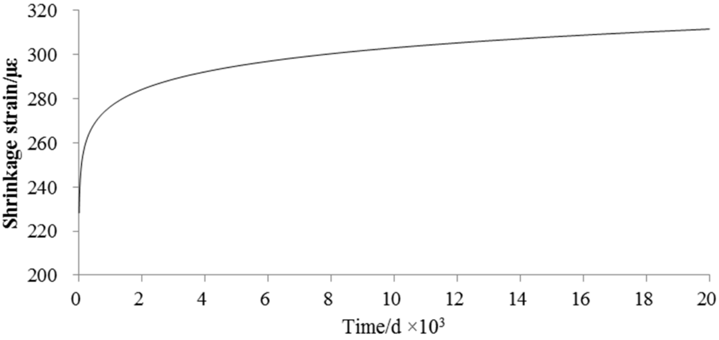

Fig. 5. Fitted curve of shrinkage strain

(3) Formwork traveller stiffness

The stiffness of the formwork traveller affects the vertical mold elevation, the shape of the construction line, and the shape of the bridge line of the main beam. The stiffness of the formwork traveller should be corrected during the construction process in order to obtain an accurate deformation value. This value will serve as a basis for correcting the elevation of the vertical mold.

When installing the formwork traveller on the Cao Lanh Cable-Stayed Bridge, the proper procedure for loading and unloading was not followed, as outlined in the construction guidelines for a standard beam section. Only 1.25 times the weight of the standard beam section was used as ballast to eliminate the inelastic deformation of the formwork traveller and assess the safety performance of the structure. Therefore, the stiffness of the formwork traveller could not be corrected before the main beam suspension construction. Since the relative stiffness of the main beam near the pylon root is large and the deformation is small, the influence of the formwork traveller stiffness error on the whole bridge alignment is also minimal[12]. Therefore, a trial calculation of the formwork traveller stiffness correction is carried out through the comparative analysis of the theoretical and measured data of each construction step of beam section 2#-4#. Finally, the correction value of the formwork traveller stiffness is 0.77 times the theoretical value.

Analysis results of the construction phase.

(1) Stress

The stress levels of the cable pylon and main beam during the construction stage and bridge completion stage are listed in Table 3. The allowable pressure and tensile stress for concrete design are 25 MPa and 4.1 MPa, respectively (as specified in the special specifications). Therefore, the stress on the cable pylon and main beam is within the required limits.

Table 3. Envelope stress of pylon and beam in construction stages and completed bridge stage

Component	Position	Max. stress of construction stages/MPa		Max. stress of completed bridge stage /MPa	
		Compressive	Tension	Compressive	Tension
Pylon	Top	19.77	2.32	17.22	0
	Bottom	16.34	3.80	15.29	0
Beam	Top	12.23	1.65	11.38	0.49
	Bottom	19.91	3.90	19.20	1.25

(2) Displacement

During the construction phase, the vertical displacement of the top of the cable pylon varies within the range of [-199mm, 592mm] (with a positive deviation in the middle span). Similarly, the vertical displacement of the main beam ranges from -777 mm to 752 mm (with positive displacement upwards). The vertical displacement of the top of the cable pylon is 58 mm, and the maximum and minimum cumulative vertical displacement of the main beam are 55 mm and -613 mm, respectively.

(3) Cable force

The maximum cable force and stress of the stay cable and temporary cable during the construction stage and the bridge completion stage are listed in Table 4. The allowable tensile stress of the stay cable design is 0.55×1860=1023 MPa (the limit value specified in the special specification). Therefore, the stress of each cable meets the requirements.

Table 4. Maximum force and stress of cable in construction stages and completed bridge stage

Component	Construction stages		Completed bridge stage	
	Force/kN	Tension	Force/kN	Tension
Stay cables	6548	883.1	6495	733.8
Temporary cables	1597	887.1	/	/

Note：Temporary Cables have been removed in completed bridge stage.

4 Alignment control

4.1 Pylon

During construction and operation, the pylon will experience both vertical and horizontal displacement due to factors such as self-weight, cable force, shrinkage, and creep. In order to ensure that the cable pylon maintains a linear shape that meets the design requirements after the bridge is completed, the construction process takes into account longitudinal pre-offsetting and vertical pre-raising. The long-term effect of the pylon includes the longitudinal pre-offsetting, which accounts for the shrinkage and creep experienced over 10,000 days from the start of construction to the completion of the bridge. The pre-offsetting (ΔL_i) is determined for each of the 33 sections of the pylon based on the negative value of the cumulative longitudinal displacement during the 10,000 days. The inclination of the pylon after topping out is controlled within a range of (ΔL_{Top}-70, ΔL_{Top}+70) mm. Vertical pre-raising is considered part of the short-term effect, which occurs from the start of pylon construction until the completion of the bridge. The pre-raising (ΔH_i) is determined for each column segment based on the negative value of the cumulative vertical displacement during the bridge construction. The elevation of each segment is controlled within a range of (ΔH_i-10, ΔH_i+10) mm. When the construction of the pylon is completed, the vertical pre-offsetting of the pylon top is 142 mm, and the vertical pre-raising is 65 mm. The difference between the measured value and the theoretical value of the vertical deflection of the top of the two pylons at each construction stage and after the completion of the bridge is kept within ±70 mm (the limit value specified in the special specification), which satisfies the specification requirements.

4.2 Main beam

Pre-camber.

The pre-camber of the main beam is set without considering the effect of automobile load and only takes into account the effect of shrinkage and creep after 10,000 days of bridge completion. The cumulative displacement of the main beam from the start of construction to 10,000 days after the completion of the bridge is shown in Figure 6. The maximum and minimum vertical cumulative displacements are 17 mm (13# beam segment of the side span) and -675 mm (14# beam segment of the middle span), respectively. The pre-camber of the main beam is shown in Figure 7. The maximum and minimum pre-camber values are 104 mm (16# beam segment in the middle span) and 6 mm (10# beam segment in the side span), respectively.

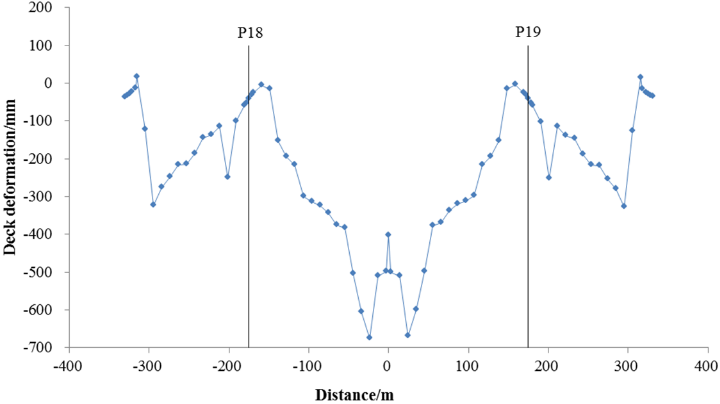

Fig. 6. Accumulative deformation of beams of 10000 days later after construction

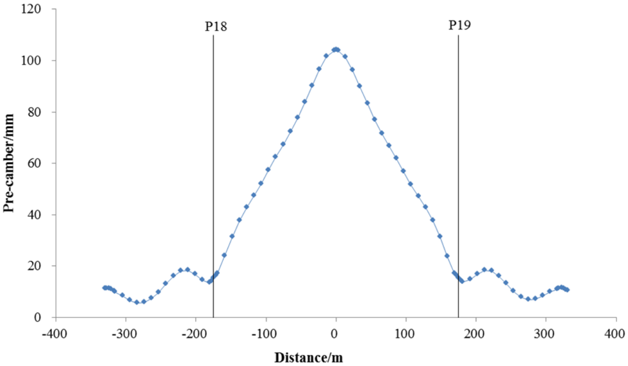

Fig. 7. Pre-camber of beams

Control accuracy.

The height error of the main beam is controlled by sections. The allowable construction error ranges for the main beam at the center line of the main span, the pylon, the maximum vertical deformation of the side span, and the side pier are as follows: [-100 mm, 170 mm], [-20 mm, 40 mm], [-60 mm, 100 mm], and [-20 mm, 40 mm], respectively. The error ranges of the remaining segments are interpolated linearly from the error ranges of the four positions mentioned above. According to the analysis of the main bridge structure, the maximum vertical deformation of the side span occurs at the front end of the 11# beam segment. The height error control range for each section of the main beam is then determined and depicted in Figure 8. As shown in Figure 8, the positive error limits for elevation are greater than the negative error limits. Additionally, the error limits generally increase with the length of the cantilever of the main beam during construction. This reflects the concept of better high-level and dynamic control, rather than low-level control.

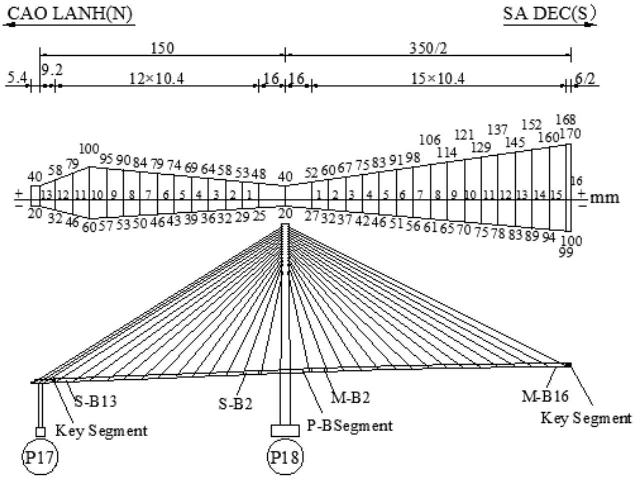

Fig. 8. Elevation error range of beams of 1/2 main bridge

Influence of temporary cable on the alignment of the main beam.

After the construction of beam section 5# was completed, temporary cables of the 1# (middle span) and 2# (side span) were installed after the middle and side span hanging baskets were moved forward. After the construction of the 10#-12# beam section was completed, the temporary cables of the 3#-5# side span were installed after the formwork travellers of the middle and side span were moved forward. Temporary side span cables (2#-5#) were removed after side span closure and before middle span 14# beam section construction; The temporary cables (1#) of the middle span were removed after the middle span was closed and before the system was converted. The temporary cable serves as a passive force, and only the initial tension that counteracts its own weight is applied during the actual construction to keep it in a tensioned state.

During the construction of the asymmetric cantilever, the temporary cable will undergo several construction stages after installation. This is done to ensure the stability and safety of the structure under the combined action of the most unfavorable unbalanced load and the maximum construction wind speed. Additionally, the temporary cable plays a role in adjusting the internal forces of the structure and aligning the main beam by changing its own cable force. After removing the temporary side span cable, the maximum elevation of the side span was increased by 109 mm, while the maximum elevation of the middle span was reduced by 110 mm. After removing the temporary cable from the middle span, the maximum elevation of the side span was reduced by 7 mm, and the maximum elevation of the middle span was reduced by 19mm. In consideration of the impact of the temporary cable on the straightness of the main beam, the installation, and tensioning should be performed based on its precise length when not under stress and initial tension.

Middle span closure control.

The length of the middle span closing section of the Cao Lanh Cable-Stayed Bridge is 6 m, which is longer than the 2 m closing section commonly used in domestic concrete cable-stayed bridges. At the same time, the construction process for the asymmetric structure involves multiple stages, and the elevation undergoes significant changes throughout the construction process. In order to ensure the smooth alignment of the main beam after the middle span closure and the proper distribution of internal forces, it is necessary to accurately control the closure alignment.

During the construction of the first three beam sections (14#-16#), the concrete bulk weight and square quantity were strictly controlled according to the design document to ensure that the self-weight of the main beam met the requirements; The construction and data testing of each key process were arranged at 2:00~6:00 AM to eliminate the influence of ambient temperature and temperature gradient. Through the comprehensive comparison and error analysis of the elevation and cable force data of the 14#-16# beam section in each construction stage, the influencing factors were separated and determined, and the main beam alignment was gradually adjusted by adjusting the mold elevation and cable force to approximate the closure target. The height difference between the two cantilever ends of the main beam was 23 mm, which did not meet the closure requirement of 30 mm. However, the alignment of the main beam met the requirement for height control accuracy after the bridge was completed.

5 Conclusion

The typical segments of the Cao Lanh Cable-Stayed Bridge adopts a design and construction scheme of an asymmetric double cantilever casting concrete by formwork traveller. Through precise structural calculation and analysis, as well as strict alignment control during the construction process, the cable pylon and main beam can achieve the required control precision for their linear shape. With the promotion of the “Belt and Road” initiative, it has become an inevitable trend for domestic enterprises to increase their output of equipment and technology. Additionally, cooperation with foreign enterprises will also become increasingly closer. A comprehensive comprehension and integration of foreign project design, construction, and other concepts are of great significance for domestic enterprises to expedite and enhance project implementation. The Cao Lanh Cable-Stayed Bridge is the first cable-stayed bridge constructed by Chinese enterprises in Vietnam. Its construction method, known as asymmetric double cantilever casting, differs from the symmetrically balanced cantilever casting method commonly used in China. This paper discusses and analyzes the structural characteristics, parameter correction methods, and linear control aspects of cable-stayed bridges constructed using this method. The aim is to provide a reference for the development of similar projects overseas.

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