

Study on construction control technology for tower and beam synchronous construction of cable-stayed bridge

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Abstract. With beautiful appearance, large span capability, and reasonable load conditions, cable-stayed bridges have been constructed widely. In this paper, combined with the specific circumstances of the project of the Dingzihekou Bridge, the construction control technology for tower and beam synchronous construction is studied. The construction method was discussed from the aspects of the influence factors, control principle and application scope of the tower girder synchronous construction. The whole, main tower, main girder, stayed cable and other control measures are put forward to ensure the reduction of construction error.

1. Introduction

In the construction, the structure system of cable-stayed bridge with multiple input and multiple output is complex and changeable[1]. Although the tower girder synchronous construction can reduce the time limit, the cost, and the budget, as the result of the overlap of the space and the times, there increases the security risk. Because of all kinds of error factors, the tower column will produce non-uniform force and increase the difficulty of displacement control of main tower, which make the construction line of main tower more difficult to control. The main tower has not yet been fully stiffness and stable, and it is difficult to determine the initial cable force. In addition, due to the synchronous construction of the main girder, especially the construction of cable-stayed cable in the main girder construction, the stress and linear disturbance will be caused to the tower column (especially the high tower), which will cause many unknown quality hidden dangers to the new pouring concrete in the later stage of the main tower. It also puts forward a higher standard for the construction control technology of the prophase pylon. Therefore, it is very important to strictly control the construction process in the case that the cable-stayed bridge adopts the tower girder synchronous construction method.

According to the measured elevation and internal force (mainly referring to the initial tension of the cable and the stress of the main beam and the key part of the pylon), the main girder type and so on, the actual data are compared with the theoretical values. By identifying the main structural parameters of the bridge, we obtained the difference principle, and then to modify the parameters[2]. With the effective measures are adjusted in the construction process, the optimal state control is carried out, and the actual control value of the next construction stage is determined.

2. Project Summary

The Dingzihekou bridge is located at the junction of Haiyang City, Yantai, and Jimo, Qingdao. The main bridge is a 88m+200m+88m double-tower double cable-stayed concrete cable-stayed bridge. After the top of the main tower is closed, the construction of the top of the tower is completed in 5 stages. To shorten the construction period and make full use of the best construction season, the 5



stages of the main tower and tower and the 1-5# section of the main beam and tower are to be used simultaneously. According to the construction plan of the main bridge, the process of the tower and beam synchronous is carried out according to Table 1-1. The total process of the synchronous construction totaled 495 days. Among them, the tower and beam synchronous construction phase was 110 days, which reduced the 90 days construction period compared to asynchronous construction.

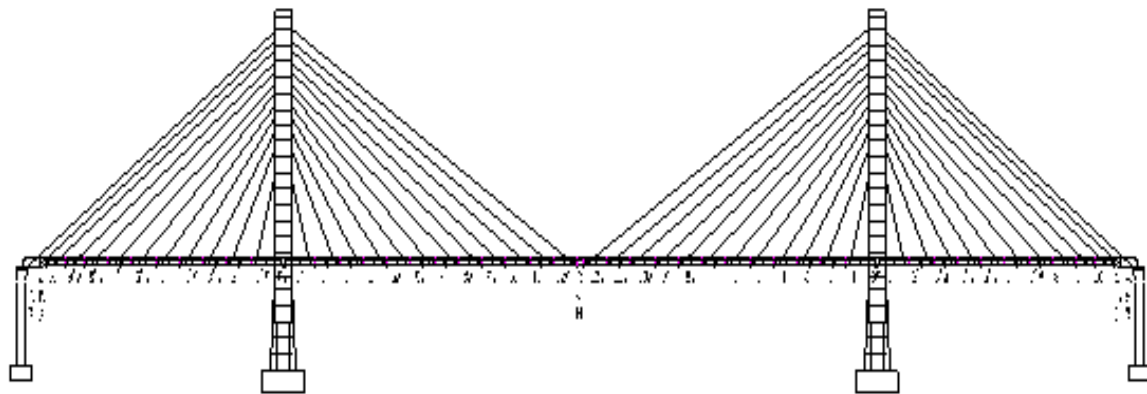


Figure 1. Schematic diagram of the bridge

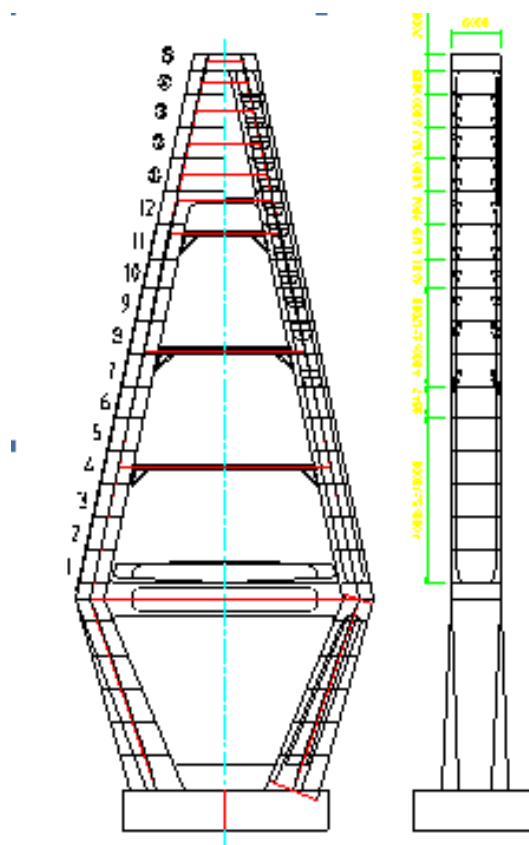


Figure 2. Schematic diagram of tower construction of main tower[mm]

Table 1-1. The steps of synchronous construction

Step	Construction step	Duration	Step	Construction step	Duration
1	Lower part of the tower and cross beam	60	12	Cable B7, Z7, 7# section of main beam, hanging basket of 8# block of main beam	15
2	1-11# section of upper art of the tower	140	13	Cable B8, Z8, 8# section of main beam, hanging basket of 9# block of main beam	15
3	12# section of upper art of the tower	20	14	Cable B9, Z9, 9# section of main beam, hanging basket of 10# block of main beam	15
4	0-1# section of main beam	20	15	Cable B10, Z10, 10# section of main beam	15
5	Cable B1, Z1, 1st closure section of the tower, hanging basket of 2# block of main beam	15	16	Side span cast-in section	15
6	Cable B2, Z2, 2rd closure section of the tower, 2# section of main beam, hanging basket of 3# block of main beam	15	17	Side span closure part, hanging basket of 11# block of main beam	15
7	Cable B3, Z3, 3rd closure section of the tower, 3# section of main beam, hanging basket of 4# block of main beam	15	18	Cable B11, Z11, 11# section of main beam, hanging basket of 12# block of main beam	15
8	Cable B4, Z4, 4th closure section of the tower, 4# section of main beam, hanging basket of 5# block of main beam	15	19	Cable B12, Z12, 12# section of main beam, hanging basket of 13# block of main beam	15
9	5th closure section of the tower	10	20	Mid span closure part	15
10	Cable B5, Z5, 5# section of main beam, hanging basket of 6# block of main beam	15	21	Bridge deck	20
11	Cable B6, Z6, 6# section of main beam, hanging basket of 7# block of main beam	15	22	Shrinkage and creep in 5 years	1825

3. Influence Factors

The calculation of the construction phase is carried out in a simplified engineering context, but in fact, there are many non-deterministic factors that affect the construction. It make the design parameters difficult to reflect the actual situation sometimes and it may even overestimate the limits of parameters in some cases, then may lead to the errors in line shape, elevation and cable force. There are many factors that affect the simultaneous construction process of tower and girder of cable-stayed bridges, mainly in the following aspects:

(1) Structural parameter: components size, elastic modulus and thermal expansion coefficient of construction materials, initial stress of steel bars and tension of cable, temporary load and so on. During the construction process, these impact parameters need to be monitored and valued immediately.

(2) Errors: errors of structural finite element model's simplification and calculation, measurement, construction, monitoring and so on.

(3) Load: there are always changes in load during construction, including the constant load (bulk weight of the material, especially, concrete), live load, temporary load (crane, hanging basket, stacking materials, tension platform) and other loads.

(4) Environment: Due to the limitations of current technical, accurate measurement of the temperature field is difficult. In addition to temperature, there are also effects of humidity, wind and rain. Especially in the cantilever phase, structural shake can easily cause linear errors and errors in the cable tension, as well as effect of concrete shrinkage and creep.

4. Principle of Control

In order to ensure the successful implementation of the construction plan, the following principles are proposed for construction control:

(1) Mechanical requirements

The factors that reflect the mechanics of cable-stayed bridges mainly include the stress and distribution (or the magnitude of internal forces in the section) of the towers, main beams and cable-stayed.

(2) Deformation requirements

When the cable-stayed bridge is completed, the linear shape of the structure should be reasonable (straight towers and beams) and meets the requirements. The elevations of the main tower and beams at various positions and the horizontal deviation of the main tower can meet the specifications and design requirements during the construction process and after long-term deformation.

5. Construction Monitoring

The monitoring of the construction stage is not only the basis for its control, but also an important means for carrying out construction monitoring, plans changing and ensuring the safety of the bridge structure[3].

The monitoring targets are mainly the elevation of the beam segment, the displacement of the tower, the cable force, the stress and strain of the control sections of the structure, and the influenced measurement of temperature. Several major monitoring contents are specifically introduced as follows:

(1) Main beam deformation: mainly refers to measure the deflection of beam segment. Specifically, the elevation of the main beam is measured before and after the main construction conditions of each section. The measurement of the elevation of the concrete after pouring and the transformation of the structural system should be completed during the time before sunrise. Secondly, the deviation of the main beam axis must be measured in time when each main beam piece is erected to correct the orientation of the main beam axis.

(2) Cable tower deformation: It is that measuring the axial displacement of towers before and after certain critical construction conditions periodically. Because the cable-stayed in the bridge adopts a fan-shaped distribution, the horizontal displacement of the tower column must also be measured, we also need to observe the horizontal displacement of the column under unbalanced load, sunshine and other influencing factors.

(3) Cable force: This bridge is intended to use spectrum analysis method to measure the cable force with the help of the instrument named "Intelligent Signal Acquisition and Processing and Analysis System". Using hydraulic jacks with strictly calibrated in tension cables to check Readings. At the same time, the time for observation of the cable forces is set at the time of major changes in the working conditions of each component.

(4) Stress and strain: It refers to the stress and strain data of the control section of some beam sections or towers before and after certain important conditions. Specifically, some representative

cross-sections are selected on the beam section and the cable tower, and the stress distribution of these sections is obtained by strain sensors.

(5) Hanging basket deformation: It refers to measuring the deformation of the hanging basket before and after the pouring of the concrete in the beam section, it can also be used as an important basis for adjusting the elevation of the main beam.

(6) Measurement of temperature's influence: under typical local climatic conditions (reference actual data), the data of one-day main beam deflection, tower column displacement, and cable force were measured as a function of temperature and aging, and the influence of temperature on the parameters was obtained.

6. Process of Control

The control process of the tower and beam synchronous construction of the Dingzihekou Bridge is roughly as follows:

(1) Referring to the design introduction, specifications and previous cases to determine various design parameters, and take the line shape as an ideal goal. Then the elevation of the first section of the main beam and the cable force during construction were predicted using finite element numerical simulation software.

(2) According to the results of the first step, the first beam section is constructed, and the variables such as the elevation of each control section of the beam section, the deformation of the tower, the cable force, and the strain are measured in time.

(3) Comparing the obtained actual values of the monitoring variables with the analysis results of the finite element simulation software to obtain the difference between them.

(4) The recognition module is used to identify and correct the obtained calculations and actual measurement results. If part of the working conditions does not require this item, go from the third step to the ninth step.

(5) According to the modified parameters, the finite element numerical simulation is performed to obtain the secondary-calculated value which is observable. And the measured value is compared with the measured value.

(6) Analyze the cause of the difference. And analyze it by using numerical simulation method with reassigned parameters. At the same time, adjust the pretension of the corresponding cable.

(7) Discuss whether the bridges is safe after the parameter is corrected. Turn to step 9 if safe, make the parameters modified once again otherwise.

(8) Adjust the target cable force of un-constructed girder to obtain a new target cable force by using target cable force of a reasonable bridge state as a reference.

(9) Analyze of the finite element numerical simulation to predict the elevation of the main beam and the cable tension of the next beam section.

(10) Carry out the next beam section construction and measure the height of each control section of the beam, the deformation of the tower, the cable tension and other variables according to the forecast value.

(11) Repeat steps(3)-(10) until the construction of the entire bridge is completed.

As the parameters of the entire bridge will be identified and corrected for several times, the value is more and more accurate with beam being constructed. The calculated value obtained by the finite element software will also be gradually approaching the aimed value. Therefore, the control system is reasonable and accurate.

7. Control Measures

Combined with the influence factors and control criteria of the cable-stayed bridge discussed earlier in this paper, the control measures of tower, cable and beam of synchronous construction method in cable-stayed bridges are proposed.

7.1. Construction Control of Entire Construction

In order to ensure that the main tower meets the design requirements, it is recommended to monitor the deformation and stress of towers and beams and cables accurately and in real time at all

construction stages and make corresponding adjustments to reduce the unbalanced moments of the tower caused by non-deterministic factors. Compare the monitoring results with the calculation results of the numerical simulation. The simulation of the structure should be accurate to ensure that the construction monitoring can detect abnormal situations in time and to help take effective measures. At the same time, as construction is in progress, the frequency of stress and displacement monitoring should also be increased.

7.2. Construction Control of Main Tower

Effective control measures must be taken to reduce the deflection of the closure sections in the top of the tower. The main towers which use synchronous construction method is more sensitive to the temporary load and the unbalanced load, resulting in a requirement of more complicated control technology. In general, the construction control method focuses on the stress and verticality of the most unfavorable position of the tower. Accordingly, the main control measures proposed for main tower of the bridge are as follows.

(1) Pay attention to controlling the influence of temporary loads and unbalanced loads on the construction, such as the stacking location of construction equipment and materials.

(2) Because the stress reserve at the lower edge of the upper part of the tower is not sufficient in synchronous construction stages, and the stability and safety factors of the tower is low, it is necessary to add temporary cross beams between tower columns to reduce the stress and displacement of and improve the overall rigidity of the tower.

(3) The permissible error of the verticality of main towers shall be within the $h/3000$ range, and no more than 30mm or design requirements after the construction of bridge towers[4]. Monitoring points should be set at multiple positions in the completed tower segment, and a high-precision local temporary measurement control network should be established to calculate the three-dimensional coordinates of the tower.

(4) Deviation-correction plan should be prepared before synchronous construction stages. The construction should be stopped immediately to find out the problems once there is a large deviation of the main tower in construction. Detailed revisions and updates are made on the basis of the prepared plan. And records should be noted to avoid cumulative errors and ensure the verticality and linearity of main tower.

7.3. Construction Control of Main Beam

(1) The elevation of the main girder is controlled by using the absolute elevation control method[5] to avoid accumulation of errors. Based on the elevation of the beam and the initial tension of the cable at the current stage provided by the monitoring department, the construction department should plus this elevation with the deformation of the hanging basket as the elevation of the bottom of the formwork. Each carload of concrete be weighed and get the actual weigh when pouring concrete.

(2) The stress control of the main beam of the bridge consists of two parts: steel stress and concrete stress. Stress sensors can be embedded in concrete to monitor the stress state of construction stages in real time in order to ensure the error between the actual stress and the design value of the girder does not exceed $\pm 5\%$.

(3) For the observation of the deflection of the upper and lower edges of the main beam, no less than three measuring points can be arranged at the end of each beam. It should be noted that in order to reduce the influence of temperature, observations should be made during the period of stable temperature. It is necessary to proceed in accordance with the order during the stages of pouring, hanging basket moving and demolition.

(4) The main beam line shape needs to be measured through both vertical and horizontal directions at the same time, in order to fully and accurately understand the real-time spatial conditions of the main beam. During the operation of the hanging basket, the jacks used in the construction must be operated synchronously.

7.4. Construction Control of Stay Cable

After starting the main girder construction, according to main tower's top displacement observation and the stress deflection of the main girder, the real-time monitoring of the cable tension is constantly feedback, analysis and correction to ensure the shape and accuracy of the tower beam meet the requirements.[6] However, if necessary, we can give up some of the cable tension accuracy, but the cable force error measured in the construction process should be in the range of numerical $\pm 10\%$.

In the process of pulling the cable, try to choose the time period of the most stable temperature in one day. When the cable is tensioned, the bridge deck requires no dynamic load, and the additional load should be in accordance with the design calculation condition as far as possible. When the last cable is tensioned, the control of the cable force and the design is within $\pm 5\%$ with the control of the main girder linear. At last, after the closure of the bridge and the completion of the two-stage paving and moving load, a unified cable is also needed to correct the deformation of the pylon.

7.5. Stability Control

The stability of large span cable-stayed bridges has been paid attention to in the whole structure and local components. However, there is no reliable monitoring means for the instability that may occur during the construction phase, and there also is no reaction means and evaluation mechanism. Therefore, further research is needed to improve this aspect.

7.6. Structural Safety Protection Control

In the construction of No. 0 and No.1 Cantilever pouring beam section, the safety hidden trouble is greatest. It is necessary to strengthen the safety consciousness of the construction personnel. Meanwhile, increasing the construction protection measures of the main tower and the main girder to ensure the safety of the construction personnel and ensure the smooth completion of the cable-stayed bridge. If the conditions permit, there could be set up safety shelter and medical related equipment. Specific protection measures can be taken as follows:

(1) The stencil working platform of the upper tower column adopts a fully-enclosed structure. The mesh with a grid spacing within 1 cm is added to the perimeter of the fence to prevent small objects from falling from high altitude.

(2) Setting up a crash-proof platform on the completed tower column, which size of each side exceeds the column template projection size of at least 2 meters. The soft material is laid on the platform, which plays a buffering role to the falling object.

(3) A protective shed for working personnel to be erection on the top of the main girder. During the construction process, the workers are required to pass through the protective shed.

(4) A protective cover is installed on the inside of the bridge tower, which is mainly used to prevent the welding spark at the top of the tower column and the falling of small objects when the cable stays on the cable.

7.7. Other Controls

In the process of the tower and beam synchronous construction, there are many construction procedures and safety risks. In addition to the control measures to ensure the above major indicators, the following control measures should also be taken.

(1) Before the start of the tower and beam synchronous construction, the production of concrete should be well done. According to the concrete strength C50, C40 and retarding time to determine the concrete mix ratio and other parameters to ensure that its elastic modulus, workability, fluidity, etc. to meet the requirements of the specification and design. During the construction period, concrete batch sample making and inspection work shall be done in time division batches, and the quality of concrete shall be strictly monitored. At the same time, according to the monitoring situation, adjusting the production technology of concrete in time to ensure that the production quality of concrete meet the requirement from the source.

(2) To minimize the effect of the temperature, construction control measurements and the precise positioning of the baskets should be carried out in the period prior to the dawn.

(3) Record the environment, load and special loads of the main construction conditions, especially to record and check the relevant data of mutation condition in detail, to ensure the safety rationality of the changed working condition.

8. Conclusion

(1) The theory of synchronous construction control system for the tower and beam of long-span cable-stayed bridge is briefly described. The construction method has its unique advantages, but it is also greatly complicated and difficult to control in construction.

(2) The main factors that may affect the synchronous construction control of tower girder were summarized, and then we provided the control direction for the construction method.

(3) The principle of the tower and beam synchronous construction was discussed from two aspects of mechanics and deformation. It was necessary to ensure that the completion of cable-stayed bridges could reach a reasonable target for completion of the bridge. So the structure needs real-time monitoring and constant correction to minimize and eliminate all factors which influence the bridge-forming target of cable-stayed bridge during construction.

(4) The main monitoring contents of the synchronous construction of the Dingzihekou Bridge were summarized, and its control system was combed.

(5) This paper puts forward the control measures of the tower girder synchronous construction method for the Dingzihekou Bridge.

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