Construction monitoring of cable stayed bridge with unequal span and single tower and single cable plane

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Abstract. In order to improve the efficiency of bridge construction, a bridge construction monitoring method based on MIDAS civil finite element software is designed in this paper. Taking the construction monitoring of the main bridge of Huangshuihe bridge on Tonghai road in Xining City as an example, the monitoring parameters of the top deflection of the main tower and the simulation of temperature change during construction are described in detail. The effectiveness of the method is verified by the comparative analysis of theoretical data and measured data.

Keywords. Cable stayed bridge; construction monitoring; unequal span cable-stayed bridge; error analysis

1. Introduction
Cable stayed bridge has become one of the fastest developing bridge types for its long span, beautiful appearance and good mechanical performance. With the development of bridge construction technology, technicians gradually realize the importance of monitoring work in bridge construction stage. Reference [1-3] monitored the construction process of cable-stayed bridge to ensure that the completed bridge meets the design state; Li Yi [4] put forward the transverse brace setting scheme for a two-way inclined pylon cable-stayed bridge, and carried out the transverse brace construction monitoring; He Xuhui [5] et al. analyzed the influence of single cantilever construction method compared with double cantilever construction method on the construction process and final completion state of railway steel truss cable-stayed bridge; Based on the stress free state method, Tan Kangrong [6] et al. carried out the whole bridge construction control of a cable-stayed bridge with the goal of manufacturing linear shape of steel box girder; Reference [7-8] has carried out research on construction monitoring concept, monitoring method and monitoring content of hybrid girder cable-stayed bridge; Gu Xuanlong [9] et al. put forward two new monitoring methods for the linear monitoring of long-span cable-stayed bridges, i.e., the method of setting stations freely by total station to measure and control the horizontal alignment of main girder, and the method of indirect height difference transmission of total station to measure and control the vertical alignment of main beam; Reference [10-11] has carried out construction monitoring for cable-stayed bridge with swivel construction.

Most of the above studies are aimed at the construction monitoring scheme of symmetrical structure, or the improvement and improvement of monitoring methods, while the research on construction monitoring of asymmetric single tower cable-stayed bridge is less. In this paper, taking an asymmetric single tower cable-stayed bridge as an example, combined with the finite element model, the construction monitoring is carried out to ensure the smooth construction of the bridge.

2. Project overview and finite element model

2.1 Bridge parameters
The main bridge of Huangshui River Bridge on Tonghai road is a cable-stayed bridge with single tower and single cable plane (double row cables) and semi floating system. The specific span arrangement is 135m + 71.5m + 38.5m. In which, the South connecting pier is No.3 pier, the main tower is No.4 pier, the auxiliary pier is No.5 pier, which is located between D8 and D9 cables, and the North connecting pier is No.6 pier.

The main girder adopts an inverted trapezoidal steel flat box girder with a top width of 37m, a horizontal section width of 20.8868m, and a beam height of 3.2m at the center line of the road. A main web with a thickness of 30mm is set at 2m on both sides of the center line of the box girder cross section to form a cable-stayed bridge anchorage area with a width of 4m; the secondary web and side web are 9.4 m and 17 m away from the center line, and the thickness is 20 mm and 16 mm respectively. In order to strengthen the wind resistance capacity, a 1.5m wide tuyere is set at the cantilever end of the main beam, which also serves as the base of the bridge deck lighting pole. Anti push steel plate frame is set at the bottom plate of box girder around the main beam opening at the main tower, and plate damping rubber bearing is set outside and a certain gap is reserved with the main tower to form the longitudinal and horizontal limiting device of main beam at the main tower.

The stay cables are arranged in dense cables, with 14 pairs of cables arranged on the main span, from south to north, the cable numbers on the south side of the main tower are numbered C14 ~ C1, and the cables on the north side of the main tower are numbered D1 ~ D14, the cable spacing is 6m or 8m, The included angle between the cable-stayed lock and the main beam is 28.466 ° to 51.479 °. The anchor end of the stay cable is set in the main tower, and the tension end is set in the main beam.

The main tower adopts a trapezoidal tower with a height of 106m. It is divided into several parts: the lower tower section and the lower tower section of the main tower, the horizontal tower body, the middle tower section, the cable section and the top section of the main tower.

The seismic fortification grade of the bridge site is grade VII, the design load is city a, and the design speed is 50km / h.

2.2 Finite element calculation model
The finite element modeling and structural analysis of the cable-stayed bridge are carried out by using the finite element software MIDAS civil. The plane model is used to simulate and analyze each construction stage, the stay cable is simulated by tension only truss element, the main beam, temporary support and main tower are simulated by beam element, and the rigid connection between main beam and cable, main tower and cable is adopted. The initial load of geometric stiffness is applied to simulate the contribution of gravity stiffness of main cable to structural stiffness, and the nonlinear problem of structure is considered in structural analysis. The finite element model is shown in Figure 1.

![Finite element calculation model of cable stayed bridge](image)

3.Key points of cable stayed bridge construction monitoring
The construction monitoring work should closely cooperate with the construction organization plan and the construction process to ensure the reliability of the data and provide a strong basis for the subsequent error analysis. For different construction stages, the monitoring focus is different:

(1) In the preparatory work stage, the data and equipment are prepared, traverse diagrams are designed and corresponding suggestions and optimization schemes are put forward through the comparison between the theoretical calculation of the simplified model and the design scheme.

(2) During the construction stage of towers and beams, the stress, temperature and deformation of bridge tower are measured and analyzed after the initial setting of concrete, and summarize the influence of temperature on each element.
During the tensioning of the stay cable, the temperature, shape and stress of each tensioning stage are tested. According to the measured results, calculate and compare the measured and theoretical data to analyze the error.

In the stage of full bridge test and summary, check whether the stress and line shape after completion are consistent with the design requirements, and analyze the error of each parameter.

Bridge construction as a complex and complicated system engineering, in order to ensure the accuracy and efficiency of information transmission in the construction control process, a set of scientific and complete information transmission process should be established in the specific work of construction control to ensure the smooth completion of construction monitoring work. The operation process of construction supervision and control is shown in Figure 2.

**Figure 2.** Operation diagram of construction monitoring

### 4. Cable force monitoring

Stay cables as important stress-bearing components of cable-stayed bridge and suspension bridge, the cable force of the stay cables is adjusted to make the tower and beam in the best stress state during design and construction. In the process of operation, the change of cable force should also be continuously monitored and adjusted in time to make it in the state of design requirements. Therefore, it is necessary to accurately measure the cable force both in the construction process and in the operation process. Only the cable force data after asphalt pavement in the last construction stage is given here, as shown in Fig. 3.

It can be seen from Figure 3 that the finite element simulation has a high degree of conformity with the actual construction, and the deviation between the measured value and the theoretical value of the cable force is within 5%, which can better meet the design requirements, and the finite element can more accurately simulate the actual engineering state; the
maximum cable force at the long span side is greater than the maximum cable force at the short span side, which is due to the longer beam body and greater deadweight on the long span side, and the cable bears more axial force.

5. Stress monitoring

5.1 Layout of measuring points

The stress monitoring of 33 sections of the main girder of the full bridge is shown in Fig. 4. Six strain gauges are arranged on the top and bottom plate of upstream box chamber, steel anchor box top and bottom plate and downstream box chamber top and bottom plate for each section, as shown in Fig. 5.

After the main beam is installed, before and after each stay cable tension and other important construction steps and the test is performed at a time when the atmospheric environment temperature is stable. Owing to the large amount of test data, only 3 / 4 of long span side stress results after asphalt pavement are given, as shown in Fig. 6.

![Figure 4. Layout of main beam sensor and deflection test](image)

![Figure 5. Layout of beam section stress sensors and deformation measuring points](image)

| Table 1. Displacement of tower top at each stage (mm) |
|------------------------------------------------------|
| construction stage | portrait | transverse | construction stage | portrait | transverse |
|---------------------|---------|------------|---------------------|---------|------------|
| 1# After cable tension | -1.60   | 0.00       | 10# After cable tension | 16.50   | 0.00       |
| 2# After cable tension | -6.50   | 0.00       | 11# After cable tension | 22.40   | 0.00       |
| 3# After cable tension | -7.70   | 0.00       | 12# After cable tension | 21.20   | 0.00       |
| 4# After cable tension | -3.00   | 0.00       | 13# After cable tension | 23.20   | 0.00       |
| 5# After cable tension | -1.20   | 0.00       | 14# After cable tension | 27.50   | 0.00       |
| 6# After cable tension | 1.60    | 0.00       | After removing the support | 29.10 | 1.00       |
| After design weight | 1.60    | 0.00       | After Paving concrete | 16.70   | 1.00       |
| 7# After cable tension | 8.30    | 0.00       | After weighting in the North | 16.70 | 1.00       |
After cable tension | 14.10 | 0.00 | After paving asphalt | 6.20 | 1.00
--- | --- | --- | --- | --- | ---
| 9#After cable tension | 18.20 | 0.00

Figure 6. Stress and deflections data comparison of main beam after asphalt pavement

It can be seen from Fig. 6(a) that the measured value is in good agreement with the theoretical value, and the error between the measured value and the theoretical value of the main beam in the whole construction stage is small, which can better meet the control requirements of the design corresponding stress; the main beam section is fully compressed, and the compressive stress of the roof is greater than that of the bottom plate, which conforms to the stress distribution law in the completion stage of the bridge.

6. Deformation monitoring

6.1 Deflection test of main girder
The observation data of steel girder deflection measurement is the direct basis for controlling the shape of the bridge. As shown in Fig. 5, two symmetrical elevation observation points Y1 and Y2 are arranged on each monitoring section to measure vertical deflection. Linear measurement is implemented when the temperature change is small and the climate is stable, so as to eliminate the irregular deformation of beam caused by sunshine temperature difference. Only the deflection test data of Y1 measuring point after asphalt pavement are given here, as shown in Fig. 6(b).

Throughout the construction stage, the measured value of the girder deflection is in good agreement with the theoretical value, which meets the control requirements of the design on the alignment; the finite element simulation is more conservative than the actual engineering, and the theoretical value of the girder deflection is greater than the measured value.

6.2 Tower top displacement
Background bridge belongs to asymmetric structure, so the offset of bridge tower should be strictly controlled in the construction process to prevent the damage of bridge tower caused by asymmetric load. Arrange the displacement section and displacement measuring points on the top of the tower and test the displacement of the tower top before and after important construction steps such as cable tensioning. The deviation of the tower top from the south is negative, and the North deviation is positive. See Table 1 for the results.

It can be seen from Table 1 that during the whole construction process, the maximum longitudinal displacement is 2.91 cm, which appears after the support is removed and meets the design requirements; the horizontal displacement of the tower top is basically 0, meeting the design requirements.
7. Temperature effect analysis

The temperature range of the external environment during the construction process is -10°C~30°C for the long construction period, which will have a non-negligible impact on the accuracy of monitoring and measurement. The influence of temperature should be considered comprehensively for the sake of exploring the impact of temperature on construction monitoring and reduce the monitoring error caused by temperature change. Therefore, in the finite element model, four working conditions of cooling 20 °C, cooling 10 °C, heating 10 °C and heating 20 °C are established for analysis, and the deflection and cable force of main beam at different temperatures are obtained, as shown in Fig. 7(a) and Fig. 7(b).

![Figure 7. Variation of main girder deflection and cable force with temperature change](image)

It can be seen from Figures 8 and 9 that the temperature has a great influence on the deflection of the main beam, and less on the cable force, and the higher the temperature is, the greater the deflection of the main beam is; the influence of the environmental temperature change on the deflection and cable force of the bridge is within the controllable range, and the influence of temperature on the actual measured value can be ignored after correction.

8. Conclusion

1) Combined with the analysis and monitoring of the background bridge, as the key component of the bridge, the stay cable has a great impact on the safety performance of the whole bridge, and special attention should be paid to the consistency of the measured value and the theoretical value in each stage during the monitoring of the construction stage, so as to ensure the safety of the whole bridge structure and completion;

2) Compared with the symmetrical structure, the displacement of the top of the main tower should be taken as one of the monitoring parameters in the construction stage of the unequal span cable-stayed bridge for the different influence of the main tower offset on the left and right spans, for the sake of preventing the damage of the tower caused by asymmetric load;

3) Thanks to the long construction period, the influence of atmospheric temperature change on the measurement results can not be ignored. The corresponding measurement results need to be corrected before calculation during the entire construction monitoring, so as to reduce the error caused by temperature changes.

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