Analysis of Stiffening Girder Erection Scheme of Single Tower and Single Span Asymmetric Suspension Bridge

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Abstract. The paper analyzes four different stiffening girder erection schemes of a single tower and single span asymmetric suspension bridge with the main span of 766m by using parameter analysis combined with finite element numerical simulation. Firstly, this paper proposes two methods to study the reasonable erection time of ground anchor suspender cables, and based on the Midas/Civil finite element software, the erection time of ground anchor suspender cables with four schemes is determined by using backward-calculation analysis method. Then the main cable deformation, cable saddle displacement, horizontal inclination of main cable, internal force of suspender cables and dynamic performance of different schemes are compared. The results show that for Scheme 3 adopted in the project, the deformation of main cable is the smallest, the change of the cable saddle displacement is more slowly, the horizontal inclination of the main cable is smaller, and the bending stiffness is larger. However, the torsional stiffness is small and the flutter stability is not as good as other schemes.

1. Introduction

Different suspension bridges have different stiffening girder erection sequences. Jihan Liu[1] pointed out in 2013 that the stiffening girder of the Jinshajiang Railway Suspension Bridge was more reasonable to be erected from the tower to the mid-span. Yuzhu Chen[2] presented in 2018 that when the stiffening girder of the Xijiang Grand Bridge was erected asymmetrically from the mid-span to the tower, the force and displacement were reasonable. Xinjun Zhang[3] introduced that Suspension bridges have better dynamic performance from the pylon to the midspan installation sequence.

The Jinsha River Bridge is a single tower and single span steel truss suspension bridge with the main span of 766m (Figure 1). The bridge has only one pylon on the Lijiang side. On Shangri-La side, it takes the mountain as a tower and the main cable is directly anchored to the rock deep inside the mountain. The ratio of rise to span of the bridge is 1/10, and the stiffening girder adopts steel truss girder with a span of 671m. There are 57 pairs of suspender cables along the bridge, and two pairs of ground anchor suspender cables MS1 and MS2 are set.
The bridge is located in a high and steep canyon. It has the characteristics of asymmetrical bridge tower, asymmetrical main cable, and long cable-free zone. Therefore, it is necessary to study the influence of different stiffening girder erection sequences on construction.

2. Scheme setting and research method

The steel truss girder is divided into 59 segments, and the segments numbers from Shangri-La side to Lijiang side are B1-B59. B1 and B59 are two segments at the girder ends, with length of 6.75m, and the other segments are 11.5m in length. B26 is a mid-span segment. The segments B1-B25 and B51-B27 are symmetrical about the mid-span segment B26, while B52-B59 are asymmetric segments.

When the segments are erected from the mid-span to the girder ends, the positions at the ends of the girder are not easy to close. Therefore, some segments at the ends of the girder are erected first, then the girder is closed at the position near the girder ends. According to the design scheme and the possible erection sequence of the girder, the following four erection schemes are drawn up. Among them, Scheme 3 is the erection sequence of girder used in the project.

- **Scheme 1**: Symmetrical erection from the girder ends to the mid-span. First the girder segments B59-B52 are erected, then B1-B25 and B51-B27 symmetrically, and finally the mid-span section B26 to complete the closing.

- **Scheme 2**: Asymmetrical erection from the girder ends to the mid-span. First B1-B25 and B59-B35 are erected, then B34-B27, and finally the mid-span section B26 to complete the closing.

- **Scheme 3**: Symmetrical erection from the girder ends to the mid-span. First the erection of girder ends B1-B3 and B59-B57 is completed, then the mid-span segment B26. Thereafter B25-B5 and B27-B47 are symmetrically erected, then B48-B55, and finally the B4 and B56 to complete the closing.

- **Scheme 4**: Asymmetrical erection from mid-span to girder ends. First the erection of girder ends B1-B3 and B59-B57 is completed, and then the mid-span girder section B26, followed by B27-B34. Then B25-B5 and B35-B55 are symmetrically erected, and finally B4 and B56 to complete the closing.

This research uses Midas/Civil finite element software to establish a reasonable completion state. Then, based on the reasonable completion state, the construction process is analyzed using backward-calculation analysis method.

3. Determine the reasonable time for installing the ground anchor suspender cables

For the convenience of erection of the ground anchor suspender cables MS1 and MS2, the stress-free length of MS1 and MS2 should be greater than the distance from the main cable to the anchor point, so that MS1 and MS2 can be installed in the stress-free state. This paper proposes two methods to study the reasonable erection time of ground anchor suspender cables:

- **Forward-calculation analysis method**: Do not care how to install MS1 and MS2, directly perform construction analysis according to the actual construction sequence. Whenever the distance from the anchor point of MS1 and MS2 to the main cable is not less than the respective unstressed cable length, this stage is the reasonable erection time for installing MS1 and MS2.

- **Backward-calculation analysis method**: It is assumed that MS1 and MS2 are installed in the last, and carry out construction analysis on the reverse process of the actual construction sequence. Whenever the vertical displacement of the main cable corresponding to MS1 and MS2 is larger than the elongation (0.066m) of MS1 and MS2 in the completion state, this stage is the reasonable time for installing MS1 and MS2.
In this paper, the construction process is analyzed by using the backward-calculation analysis method. Assuming MS1 and MS2 are installed in the last construction stage, the entire construction process can be divided into a total of 39 construction stages CS1-CS39.

The vertical displacement compared to the completion state of the main cables corresponding to MS1 and MS2 is shown in Figure 2.

![Figure 2. Vertical displacement of the main cable corresponding to MS1 and MS2](image)

MS1 and MS2 in Scheme 1 can't be installed in the stress-free state. Scheme 2 can install MS1 and MS2 in the stress-free state in the CS5-CS12 stages. Schemes 3 and 4 can install MS1 and MS2 in the stress-free state only in the CS5 stage. It can be found that the time to install MS1 and MS2 in the stress-free state mostly occurs in the early stages of construction, which is also determined by the asymmetry of the stiffening girder. In order to carry out the next analysis, it is necessary to determine the time of the erection of MS1 and MS2. Because the shape of the main cable is relatively easy to change, so MS1 and MS2 of Scheme 1 are installed during the unloaded cable period (CS2 stage). MS1 and MS2 of Schemes 2, 3 and 4 are installed in the CS5 stage.

4. Comparative analysis of the results

4.1. Main cable deformation and cable saddle displacement

The non-linear deformation of the main cable of the suspension bridge during construction is relatively obvious [6]. Therefore, when the steel truss girder is erected, the change of the main cable shape should be as small as possible. The vertical displacement changes compared to the completion state of the main span and side span lowest points are shown in Figure 3.

![Figure 3. Vertical displacement of the main cable lowest point](image)

It can be seen from Figure 3 that the main span lowest point displacement of Schemes 1 and 2 increases first and then decreases, while the displacement of Schemes 3 and 4 decreases first and then increases. Among them, the displacement of Scheme 3 is the smallest. For the lowest point displacement of the side span, the change is smaller than that of the main span, and the change of Scheme 3 is relatively moderate.
The horizontal displacement of the main cable saddle and the composite cable saddle is shown in Figure 4.

![Horizontal displacement of the cable saddle](image)

Figure 4. Horizontal displacement of the cable saddle

The changes of the displacement both of the main cable saddle and the composite cable saddle have the same trend. And the changes of the displacement of Schemes 3 and 4 are much gentle.

4.2. Horizontal inclination of main cable at saddle

During the erection of steel truss girder, if the horizontal inclination of the main cable on the cable saddle side is too large, the main cable will be close to the bridge tower or cable saddle foundation and may damage the main cable. The changes of the horizontal inclination of the main cable near the saddle are shown in Figure 5.

![Horizontal inclination of cable saddle](image)

Figure 5. Horizontal inclination of cable saddle

Regarding the horizontal inclination of the main cable near the composite saddle, for the four schemes, it increases first, then decreases, and the maximum values are similar. In regard to the horizontal inclination of the main cable near the main cable saddle, for Schemes 1 and 2, it increases first and then decreases, while for Schemes 3 and 4, it decreases first and then increases. The horizontal inclination of the main cable at the saddle of Scheme 3 is the smallest.

4.3. Internal Force of Suspender cable

During construction, the changes of the cable force of MS1 and MS2 cable are shown in Figure 6.

![Force of ground anchor suspender cables during construction](image)

Figure 6. Force of ground anchor suspender cables during construction
The maximum cable force of conventional suspender cables is shown in Figure 7.

![Figure 7: Maximum force of conventional suspender cables](image)

4.4. Dynamic Performance

The bending vibration frequency and torsional vibration frequency of the structure change with construction as shown in Figure 8.

![Figure 8: Frequency changes](image)

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The bending vibration frequency and torsional vibration frequency of the structure change with construction as shown in Figure 8.

![Figure 8: Frequency changes](image)

The change trend of the ratio of the torsional frequency to bending frequency is shown in Figure 9.

![Figure 9: Frequency ratio changes](image)
The length of main girder has little effect on the bending frequency, while it has large effect on the torsional frequency. The bending frequency during construction is reduced by 18% compared to the closing phase, and the torsional frequency is reduced by up to 79%. That is because the bending stiffness of the suspension bridge is mainly provided by the gravity stiffness of the main cable. The girder mainly combines the main cable to resist the torsional deformation of the structure.[7]

The bending stiffness of Schemes 3 and 4 is greater than that of Schemes 1 and 2 at the early stage, and it decreases slightly at the later stage. The bending stiffness has increased significantly during closing. The four schemes have the same change trend in torsional frequency, and all of them increase gradually as the length of the main girder increases. Commonly, The larger the ratio of the torsional frequency to the bending frequency is, the better the flutter stability of the structure.[8] Therefore, the flutter stability of Schemes 1 and 2 is better at the early stage of construction, while the flutter stability of Schemes 3 and 4 is better at the later stage of construction.

5. Conclusions
(1) This paper proposes two methods to determine the reasonable installing time of MS1 and MS2. Based on the Midas/Civil finite element software, the installing time of MS1 and MS2 of four schemes is determined by using backward-calculation analysis method.

(2) The vertical displacement of lowest point of the main cable of Scheme 3 is the smallest. At the later stage of construction, the displacement of the cable saddle in Scheme 3 changes more slowly, and it is easier to control during construction. The horizontal inclination of the main cable near the saddle in Scheme 3 is the smallest.

(3) Among the four different erection schemes, the MS1 of Scheme 3 withstands the tensile force earliest, and the cable force changes most slowly. The cable force of MS2 fluctuates, but overall it increases. The maximum and average values of the conventional suspender cable force in Schemes 3 and 4 are smaller than those in Schemes 1 and 2.

(4) The erection length of the steel truss girder has little effect on the bending stiffness, mainly affecting the torsional stiffness and flutter stability. The bending stiffness of Schemes 3 and 4 first increases and then decreases, and the bending stiffness increases significantly when closing, while the bending stiffness of Schemes 1 and 2 gradually increases. As the length of the girder increases, the torsional stiffness and flutter stability of the four schemes become larger gradually.

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