Research on Optimization of Hoisting Sequence of Main Girder of Asymmetric Long-span Suspension Bridge

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Abstract: With the emergence of asymmetric long-span suspension bridge, it is necessary to study the optimization of hoisting sequence of the main girder of this type of suspension bridge. According to the relationship between the lifting sequence of the main girder and the pushing scheme of the pylon, the method flow of optimizing the lifting sequence of the main girder of the asymmetric long-span suspension bridge is given. Taking an asymmetrical long-span suspension bridge in Guangdong Province as an example, this method is used to optimize the hoisting sequence of the main girder and put it into practice. Good results are obtained and verified: the hoisting of the main girder should be carried out from the middle of the span to the two pylons, and the hoisting speed of the middle side span should be consistent with the proportion of the standard beam sections of the middle side span, and the maximum allowable deviation of the pylon and the main girder should be used in the jacking scheme of the pylon. The hoisting sequence shall be formulated based on. It can provide a useful reference for the hoisting of the main girder of the same type suspension bridge and the suspension bridge with slings on both sides of the bridge.

1. Force analysis of the pylon
Suspension bridges have strong spanning capabilities and become the first choice for long-span bridges in my country. In order to adapt to the various and complex features of my country’s topography, asymmetric long-span suspension bridges with slings on only one bank have begun to appear.

As we all know, when the suspension bridge is hoisting the main girder, the tension of the main cable changes with the increase of the hoisting girder section, which destroys the equilibrium state of equal horizontal components of the main cable on both sides of the main saddle, causing the top of the pylon to move for readjustment. The force of the main cable on both sides of the main cable saddle finally reaches a new equilibrium state of the horizontal component of the main cable. When only the mid-span beam section needs to be hoisted, the pylon will only move towards the mid-span in one direction. In order to ensure the stress safety of the most unfavorable section at the bottom of the pylon, it is only necessary to control the maximum offset of the pylon in one direction. However, for an asymmetric long-span suspension bridge, in addition to the mid-span beam section, the side span also has a hoisting
beam section, which will cause the pylon to move correspondingly to the mid-span and side span. Also to ensure the stress safety of the most unfavorable section at the bottom of the pylon, it is necessary to control the maximum offset of the pylon in two directions at the same time, which greatly increases the difficulty of construction and control.

In addition, because the pylon can only be pushed in one direction of the side span, formulating a reasonable hoisting sequence of the main beam becomes the key to ensuring the safety of the pylon and achieving the goal of bridge formation.

2. Optimization method flow of main beam hoisting sequence

2.1. The maximum allowable deviation of the pylon is determined
According to the requirements of relevant codes and combined with concrete strength conditions, the following control indexes of the most unfavorable stress at the bottom of the pylon are available for selection:

1) no tensile stress appears in the bottom section of the pylon;
2) there is no tensile stress in the bottom section of the pylon and the compressive stress is less than 0.5 times the standard value of axial compressive strength;
3) the tensile stress of the bottom section of the pylon is not more than 0.7 times the axial tensile strength and the compressive stress is less than 0.5 times the axial compressive strength standard value.

In general, in order to ensure sufficient safety redundancy for the stress of the most unfavorable section at the bottom of the pylon, Article 2) is used as the control index in construction control, and the bare pylon model is used to calculate the maximum allowable deviation.

2.2. Optimization of main beam hoisting sequence
According to the actual construction situation, the main beam hoisting sequence is initially drafted. According to the hoisting sequence, the forward installation and upside-down demolition construction simulation calculations are performed without considering the pylon push, and the deviation values of the pylon for each lifting condition are obtained. Then, combined with the maximum allowable offset value of the pylon, the pylon push plan is drawn up, and then the construction simulation calculation of the forward installation and reverse dismantling considering the pylon push is performed. If the linear calculation result of the pylon of the completed bridge reaches the control target, the hoisting sequence is a reasonable sequence. Otherwise, it will continue to adjust and optimize the hoisting sequence, and then repeat the next cycle calculation, until the linear calculation result of the pylon of the bridge reaches the control target. The method flow of the optimization of the hoisting sequence of the main girder of an asymmetric suspension bridge is shown in Figure 1.
3. Project example
Taking an asymmetric long-span suspension bridge in Guangdong as an example. The bridge has a mid-span of 738 meters and 50 beam sections. The north span is 202 meters and has 16 beam sections. The layout of the bridge type and main beam section is shown in Figure 2.

3.1. Hoisting sequence drafting
Under normal circumstances, the suspension bridge main girder is hoisted with two propulsion methods: from the middle of the span to the pylon and from the pylon to the middle of the span. According to these two propulsion methods and the ratio of the number of standard beam sections in the mid-span, three hoisting schemes are drawn up: scheme one hoisting 4 pieces for each mid-span, hoisting one piece...
at the side span, and advancing from the middle of the span to the pylon; scheme two hoisting each mid-span 4 pieces, 1 piece is hoisted on the side span, and pushed from the pylon to the middle of the span. Scheme 3 The mid-span is first hoisted with 24 pieces, then each mid-span is hoisted with 1 piece, and the side-span is hoisted with 1 piece, and then advance from the middle of the span to the pylon. The schematic diagram of the three schemes is shown in Figure 3, and the working conditions of each scheme are divided in Table 1.

![Figure 3. Three main beam hoisting and advancing options](image)

**Table 1. Drafting of main beam hoisting sequence**

| Construction conditions | Option I | Construction conditions | Option II | Construction conditions | Option III |
|-------------------------|---------|-------------------------|----------|-------------------------|-----------|
| 1                       | Pylon construction | 1 | Pylon construction | 1 | Pylon construction |
| …                       | … | … | … | … | … |
| 6                       | Hoisting Z25/Z26 | 6 | Hoisting T2 | 6 | Hoisting Z25/Z26 |
| 7                       | Hoisting Z24/Z27 | 7 | Hoisting B15/T1/Z1 | … | … |
| 8                       | Hoisting B1/B2 | 8 | Hoisting Z2/Z49 | 16 | Hoisting Z15/Z36 |
| …                       | … | … | … | … | … |
| 36                      | Hoisting Z5/Z46 | 10 | Hoisting B14 | 18 | Hoisting B1/B2 |
| 37                      | Hoisting Z4/Z47 | … | … | … | … |
| 38                      | Hoisting B12 | 38 | Hoisting Z22/Z29 | 37 | Hoisting B15/T1/Z1 |
| 39                      | Hoisting B15/T1/Z1 | 39 | Hoisting Z23/Z28 | 38 | Hoisting T2 |
| 40                      | Hoisting T2 | 40 | Hoisting B4 | 39 | Hoisting Z4/Z47 |
| 41                      | Hoisting Z2/Z49 | 41 | Hoisting Z24/Z27 | 40 | Hoisting Z2/Z49 |
| 42                      | Hoisting B14 | 42 | Hoisting B3 | 41 | Hoisting B12/B14 |
| 43                      | Hoisting Z3/Z48 | 43 | Hoisting Z25/Z26 | 42 | Hoisting Z3/Z48 |
| 44                      | Hoisting B13 | 44 | Hoisting B1B2 | 43 | Hoisting B13 |

![…](image)

### 3.2. Pylon offset calculation

Midas Civil was used to carry out the simulation calculation of the formal installation according to the hoisting sequence of the three schemes without considering the pylon push. Considering the convergence problem of the formal installation calculation, the main cable saddle and the pylon adopt temporary consolidation constraints during the whole hoisting process, and the main girder element is
passivated to convert its weight into node load and add it to the corresponding hoisting point of the main cable. This processing method will cause certain errors in the calculation results of the main cable shape, and even make the most unfavorable section stress at the bottom of the pylon appear tensile stress, but it has little effect on the calculation results of the displacement of the pylon top. The purpose of this calculation is to obtain the pylon offset data for each lifting condition without considering the pylon push.

![Diagram of finite element calculation model](image)

Figures 5 to 7 respectively show the pylon deflection results obtained by the simulation calculation of the forward installation for the three lifting schemes without considering the jacking construction. In the figure, the negative value of the north pylon is on the north span side, the positive value is on the mid span side, the negative value of the south pylon is on the mid span side, and the positive value is on the south span side.

The variation range of the North Pylon's offset in Option I is between -0.098m and +0.910m, and the South Pylon's offset variation range is between -0.678m and +0.075m.

![The calculation result of the displacement of the pylon in option I](image)

In the Option II, the deviation range of the north pylon is between -0.098m and +1.446m, and the deviation range of the south pylon is between -0.881m and +0.075m.
3.3. Drawing up the push plan

The pre-deflection of the main saddle of the north pylon of the bridge is 1.160m, and the pre-deflection of the main saddle of the south pylon is 0.810m.

Taking Article 2) as the control index, calculated and analyzed through the bare pylon model, the maximum allowable offset value of the north and south pylons are both 0.306m. According to the calculation results of the pylon deflection and the maximum allowable deflection value of each scheme, the corresponding jacking scheme can be formulated, see Table 2.

| Pushing condition | Option I(mm) | Option II(mm) | Option III(mm) |
|-------------------|--------------|---------------|----------------|
| 1st push of the North Pylon | Cable installation /200 | Hoisting Z6Z45/330 | Cable installation /200 |
| 2nd push of the North Pylon | Hoisting Z25Z26/300 | Hoisting Z9Z42/150 | Hoisting Z25Z26/300 |
| 3rd push of the North Pylon | Hoisting Z21Z30/260 | Hoisting Z13Z38/320 | Hoisting Z23Z28/300 |
| 4th push of the North Pylon | Hoisting Z19Z32/400 | Hoisting Z17Z34/310 | Hoisting Z20Z31/160 |
| 5th push of the North Pylon | / | Hoisting Z22Z29/50 | / |
| 1st push of the South Pylon | Hoisting B1B2/300 | Hoisting B12/200 | Hoisting B1B2/300 |
3.4. Simulation calculation of jacking construction

As shown in Figure 8, a rigid beam with high rigidity is used to simulate the jacking support at the center of the pylon, and the rigid rod with the same high rigidity is used to connect the IP point of the cable. The unstressed length of the rigid rod is modified to simulate the top Push working conditions. Figures 9 to 11 respectively show the pylon deflection results obtained by the simulation calculation of the front installation for the three options considering the jacking construction.

![Finite element simulation of jacking condition](image)

**Figure 8. Finite element simulation of jacking condition**

It can be seen from Fig. 9 that in the whole process of hoisting according to Option I: the deviation of the north and south pylons under each working condition did not exceed the maximum allowable deviation value. The jacking construction of the south and north pylons is mainly concentrated in the early stage of hoisting, and the small friction that needs to be overcome is beneficial to the jacking construction. When the main beam is closed, the south pylon side span is 0.133m, and the north pylon side span is 0.171m, which is very beneficial to the subsequent phase two paving construction and operation. Comprehensive consideration Option I is the optimal hoisting plan.
It can be seen from Fig. 10 that in the whole process of hoisting according to the Option II: the deviation of the north and south pylons under each working condition did not exceed the maximum allowable deviation value. However, most of the North Pylon's jacking construction is carried out in the middle and late stages of hoisting, and the friction that needs to be overcome makes jacking construction more difficult. After the main girder is closed, the south pylon is biased toward the mid-span by 0.016 m, and the north pylon is also biased toward the mid-span by 0.156 m, which is also disadvantageous for the subsequent second-phase paving construction and bridge operation. Comprehensive consideration of Option II is relatively unreasonable.

It can be seen from Figure 7 that in the whole process of hoisting according to Option III (without considering the jacking): in hoisting Z14/Z37 working conditions, the accumulative offset of the north pylon to the mid-span is 1.503m, which means that even if the north main cable saddle The pre-deflection amount of 1.160m was fully pushed out, and the mid-span was also biased to 0.343m, exceeding the maximum allowable offset value of 0.306m. Then continue hoisting to the closed condition, the north pylon will be offset by 0.765m to the side span (in the closed condition, the north pylon is offset by 0.738m to the mid-span, 1.053m-0.738m=0.765m), because the pylon cannot move to the mid-span Pushing, this means that when the dragon is closed, the north pylon will be biased to the side span of 0.422m (0.765m-0.343m=0.422m), which also exceeds the maximum allowable offset value of 0.306m. It can also be seen from Figure 11 that during the entire hoisting process, the offset of the north pylon in some working conditions has exceeded the maximum allowable offset value, so Option III is the most unreasonable hoisting scheme and should be excluded first.
3.5. Line after closing

Based on the description in Section 3.4, choose the best plan one, the main beam hoisting plan and put it into practice. During the whole main beam hoisting process, the deviations of the north and south pylons under each working condition did not exceed the maximum allowable deviation value, and the safety of the most unfavorable section stress of the pylon was well guaranteed. After the main beam is closed, the linear shape is beautiful. The measured deflection side span of the north pylon is 0.196m, and the measured deflection side span of the south pylon is 0.121m, which is in good agreement with the theoretical value and fully achieves the linear control goal of the pylon.

4. Conclusion

According to the method and process of determining and optimizing the hoisting sequence of the main girder of an asymmetric long-span suspension bridge given in this paper, an asymmetric long-span suspension bridge in Guangdong is used as an example to verify the implementation, and finally the bridge has a good shape. From this, the following conclusions can be drawn:

1) The hoisting sequence of the main girder should be formulated and optimized with the maximum allowable deviation of the pylon and the bridge alignment of the pylon as the main control factors;
2) The pylon can only be pushed in one direction, so the pylon pushing plan should be formulated based on the maximum allowable deviation of the pylon and the main beam hoisting sequence;
3) The hoisting of the main girder should be advanced from the middle of the span to the two pylons. This kind of advance sequence has a larger amount of jacking in the early stage and a smaller amount of jacking in the later stage, which is more beneficial to the jacking construction;
4) The hoisting and advancing speed of the main girder of the mid-span shall be kept in proportion to the number of standard girder sections of the mid-span;
5) The above conclusions are also applicable to the determination and optimization of the hoisting sequence of the main girder of a suspension bridge with slings on both sides of the bank.

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