Stability analysis of braced structures under jacking construction of large span steel truss bridges

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Abstract. In this paper, the integral jacking control technology is innovatively proposed based on the renovation project of the Pudong Canal steel truss bridge in Luoshan Road Longdong Avenue-G1501 section in Shanghai. The steel trusses have complex loading effects on the support during jacking construction, so the stability of the support and foundation structure is under great threat. By establishing a steel truss bridge-support finite element model, the stresses of support structures under combined loads are studied, and a random combination of settlement is used to provide a theoretical basis for support compensation control. In the real project, the monitoring results match well with the finite element calculation results. In the project, the maximum settlement should be controlled to be less than 20 mm and the uneven settlement less than 5 mm, and the settlement difference between adjacent support needs to be reduced by settlement compensation devices when the settlement is larger.

1. Introduction

To reduce the influence of bridge construction on the surrounding environment, different construction methods are often selected according to the characteristics of the bridge, and the integral jacking method is an excellent scheme for the construction of short-distance river-crossing bridges. The integral jacking method has the advantages of low cost, simple equipment, strong applicability, and continuous operation, which can ensure the accuracy without affecting the existing navigation or traffic[1], so it has been widely used in the construction of steel truss bridges [2].

The stability of the support plays a vital role in the deflection control and anti-overturning of the bridge during the incremental jacking of the steel truss. Many scholars have studied the stability analysis of bridge supports. Fang Leilei relies on a large span steel box girder, using the finite element model to analyze the bearing performance of temporary pier in the process of integral jacking construction, and studies the influence of the thickness and diameter of the support steel pipe on the stress and displacement of the temporary pier [3]. Based on the steel arch steel box continuous beam composite bridge project, Liu Ziyang monitors and measures the stress state of the temporary project, and uses the temporary pier monitoring data to compare and analyze the factors that may affect the stability [4]. Wang Qin took a bridge as the research object to analyze the mechanical behavior of each component of the prefabricated platform, and studied the optimal spacing of the sliding support pier arrangement and the influence of the temporary pier settlement on the internal force of the main beam, which finally solved the problem of setting the optimal position of the temporary pier in the...
incremental jacking construction [5]. Xiao Yaming used finite element software to calculate and analyze the steel truss bridge incremental jacking construction process, studied the design method of steel support and the comprehensive analysis and calculation of steel support in each stage of construction [6]. On the basis of predecessors, Huang Honghui takes a bridge as an example to study the structural optimization of the guide girder. It is concluded that if the maximum deflection of the front end of the guide girder is too large, the maximum deflection can be reduced by extending the anchorage point position of the prestressed beam at the top edge of the guide girder [7]. Li Huimin established the overall model of steel box girder to study the changes of reaction force, deformation and combined stress of steel box girder during assembly and jacking [8]. Heya studied the variation of the deflection displacement of the front end of the guide beam in the jacking process by establishing the overall model of the steel box beam [9]. According to the literature, the current research on the construction stability of the bridge jacking method is mainly focused on the stability of the steel truss bridge structure itself and the concrete bridge support in the incremental jacking construction. The research on the influence of support settlement on the stability of the support in the steel truss jacking construction is very limited. Therefore, based on the Pudong Canal steel truss bridge of Longdong Avenue, this paper establishes a three-dimensional model to study the influence of the stress and settlement of the support on the structural stability under the combined load generated by the jacking construction, puts forward the active compensation control standard of the support settlement, and verifies the accuracy of the simulation study combined with the field monitoring data to ensure the safety of the project.

2. Engineering background and control standards

2.1. Engineering and geology

The Pudong Canal Bridge on Longdong Avenue is a single-span 120 m double-layer steel truss girder bridge. During the incremental launching process, the maximum weight of a single deck is 2840 T. The overall jacking construction technology is adopted, and the jacking is carried out every time a section of assembly is completed. The assembly area is fixed at the end of the steel truss, effectively enhancing the safety and quality control effect. The jacking process is carried out on the support, the height of the support is 6 m, the support is arranged on the east and west sides of the canal, and the 30 m channel is reserved in the middle for canal navigation.

The terrain along the project is not undulating, and the elevation of the current road is generally 4.17 m ~ 5.59 m. Outside the scope of the current road, the filling in the river is local plain filling, local gray black bottom silt, loose soft and uneven soil. Longdong Avenue is busy. It is important to note that there are a large number of underground pipelines under the road and greening on both sides, including water supply pipes, gas trunks, power exhaust pipes, combined sewer and air oil pipe etc., as shown in Figure 1, and geological profile as shown in Figure 2.

![Figure 1. Pipeline distribution](image1)

![Figure 2. Geological section](image2)

2.2. Engineering control standards
According to the prior period design requirements, it is necessary to focus on the structural stress during the incremental launching construction of steel truss, including the stress of steel truss beam and the stress of steel pipe support. During the jacking process, it should be ensured that the stress on the steel truss beam is less than 270 MPa and the permitted uneven deflection difference is less than 69 mm, and the stress on the track beam is less than 190 MPa and the permitted uneven deflection difference should be controlled at 15.6 mm. The stress of steel pipe support is less than 158 MPa, and the allowable uneven deflection difference should be 20 mm as the upper limit to ensure the safety of construction and ensure that the final bridge state meets the design expectations.

3. Numerical simulation scheme and model

3.1. Simulation scheme

This paper uses finite element software to divide the whole jacking process into fourteen working conditions according to the engineering sequence, and calculates the maximum reaction force of the support under each working condition by establishing the overall model of steel truss bridge and support, so as to obtain the maximum settlement of the support at this time. Using stochastic analysis of support settlement simulation method, further approximates the real project force situation, and obtains the maximum reaction force and stress of support under the combination of settlement through the random combination of support settlement, which provides the basis for the subsequent standard development and compensation control.

3.2. Support settlement simulation method based on random analysis

Due to the uncertainty of geological conditions and the dynamic change of reaction force in the jacking process, the relatively static simulation steps of finite element cannot accurately predict the accurate value of settlement. In the study, the random analysis method is used to obtain the support stress and reaction force closer to the real project through the random combination of settlement, which is used as the subsequent compensation standard. The main analysis steps are shown in Figure 3. In the analysis, it is necessary to simulate the uneven settlement of the real project by randomly combining the settlement of different blocks, so as to obtain the stress results of the steel truss under the most unfavorable state.

![Figure 3. Simulation approach](image)

3.3. Numerical model

In order to accurately simulate the support stress during the jacking process of steel truss bridge and calculate the stress and deformation settlement of the support under each working condition, the 3D finite element software was used to establish the refined model of the support structure and slide beam of the steel truss bridge as shown in Figure 4. The steel truss bridge model has a total length of 120 m and is assembled by five-section steel trusses. The length×width×height of each truss bridge model is 24m×7.4m×2m, weighing about 71.3 tons, the model uses the displacement constraint in Z-axis direction and the displacement in X-axis direction as the boundary condition. In the modeling process,
some of the models are reasonably simplified with the actual project, for example: (1) Ignoring the influence of welding joints on structural forces; (2) Ignoring the influence of wind loads and other vibration loads on the structure during the jacking process.

Support details

Figure 4. Integral model of steel truss bridge-support

3.4. Numerical simulation
The jacking of steel truss bridge is a continuous process. In the simulation, the jacking construction of steel truss bridge is roughly regarded as three cycles: truss assembly, truss jacking, and truss jacking completed, so as to study the stress of the support. The whole assembly process is divided into fourteen working conditions. The first section is assembled as the first working condition shown in Figure 5, the first section is jacking as the second working condition, and the first section is completed as the third working condition. In this way, the fifth section of the steel truss is assembled as the working condition thirteen, and the whole jacking is completed as the working condition fourteen.

Figure 5. The first section is assembled

4. Calculation results and validation

4.1. Analysis of calculation results of support reaction force
The maximum reaction force distribution of each working condition under standard combination is calculated by finite element software, and the maximum reaction force results of each working condition are shown in Figure 6. According to Code for design of building foundation (GB50007-2011), the settlement corresponding to the maximum reaction force is calculated, as shown in Figure 7.
6. Counter force plot

From Figure 7, it can be seen that the stress and settlement of the support have a large mutation during the eleventh to the twelfth working conditions. The main reason is that the steel truss bridge is in the river crossing stage, as shown in Figure 8, there is no support on the river surface, so the stress area of the river bank support is greatly reduced, and the stress of the support increases sharply, which causes the settlement of the support to increase sharply. During the whole jacking period, the settlement of the support is basically distributed between 10 mm and 30 mm, most of the settlement is about 20 mm, and the settlement is large. It is necessary to reduce the settlement and improve the engineering quality by other ways.

4.2. Calculation results of support settlement corresponding stress

Since the three typical working conditions of fourth section installation (working condition A), fifth section installation (working condition B) and fifth section jacking (working condition C) are the most unfavorable working conditions in the cross-river stage, a targeted study of these three working conditions was carried out using stochastic analysis, and the schematic diagram of the working conditions is shown in Figure 9. The support were divided into seven different settlement areas as shown in Figure 9 based on the principle of similar reaction forces or the proximity of the support system. In the study of uneven settlement on support reaction force and steel tube stress, two cases of maximum settlement difference of 5 mm and 20 mm in adjacent areas were studied separately. The following stress calculation results show that the reaction force deviates greatly from the standard under the combined mode of two kinds of uneven settlement, and the stress distribution of the steel pipe is 50.6 MPa ~ 112.7 MPa when the uneven settlement is 20 mm. Combined with the engineering control standard, the stress in the case of settlement difference of 5 mm is within a reasonable range, and the stress in the case of settlement difference of 20 mm may exceed the limit. Therefore, the uneven settlement of adjacent supports is not more than 5 mm as the control standard, and it is controlled according to the standard that the overall maximum settlement is not more than 20 mm.

4.3. Calculation of stress distribution of adjacent supports

Table 1. Calculation results of stress and reaction force

| Maximum reaction force of the support (kN) | Maximum settlement | Condition A | Condition B | Condition C |
|-------------------------------------------|-------------------|-------------|-------------|-------------|
| 5 mm settlement                           | 1864.7            | 1813.3      | 1482.7      |             |
| 20 mm settlement                          | 4663.4            | 4685.5      | 3212        |             |
| Corresponding steel pipe stress           | 5 mm settlement   | 28.0        | 27.2        | 14.7        |
The above stress calculation results show that the reaction force deviates greatly from the standard under the combined mode of two kinds of uneven settlement, and the stress distribution of the steel pipe is 50.6 MPa ~ 112.7 MPa when the uneven settlement is 20 mm. Combined with the engineering control standard, the stress in the case of settlement difference of 5 mm is within a reasonable range, and the stress in the case of settlement difference of 20 mm may exceed the limit. Therefore, the uneven settlement of adjacent supports is not more than 5 mm as the control standard, and it is controlled according to the standard that the overall maximum settlement is not more than 20 mm.

5. Study on monitoring and compensation of support settlement

5.1. Field monitoring of support settlement

5.1.1. Monitoring
Due to the large settlement of the support across the river, it is necessary to continuously monitor the settlement of the support, and propose compensation measures based on settlement. Because the reaction force is greatly affected by random settlement deformation, in order to accurately grasp the deformation condition, it is necessary to adopt the layout scheme of densely distributed measuring points. By arranging elevation observation points on the side of the support and recording the settlement data after each construction process, the specific observation points are shown in Figure 10.

Figure 10. Marking layout of measuring points

5.1.2. Compensation
In order to better compensate the elevation, this paper proposes to set a wedge block with adjustable height between the steel pipe support and the track beam, as shown in Figure 11. The left and right parts are tightened by tension bolts, and the maximum adjustment height is 6 cm. The device can adjust different heights by adjusting the angle between the size of the component and the inclined plane. After the wedge block is under pressure, namely, the initial height is measured, and the adjustment should be adjusted in stages with 5 mm as an order of magnitude, and the scale method is used for review.

5.2. Site subsidence monitoring results
The jacking process of the whole project is divided into eight steps according to the construction key points, so as to study the influence of settlement compensation on construction. The main construction steps are: the first section jacking completed as the first step, the second section jacking completed as the second step, the second section is completed and the third section is prepared for adjustment as the third step, the third section jacking completed as the fourth step, the third section is completed and the fourth section is prepared for adjustment as the fifth step, the fourth section jacking completed as the sixth step, the fifth section is installed as the seventh step, and the fifth section jacking completed as the eighth step. The arrangement of site support observation points is shown in Figure 12.
The filing monitoring data show that the monitoring points have different degrees of settlement deformation, and the maximum settlement deformation of ZJ01~ZJ12 support is within 17 mm. The maximum settlement deformation of ZJ13~ZJ18 support is within 15 mm, which is not more than 20 mm. Among them, ZJ1~ZJ12 support experienced two adjustments as shown in Figure 13:

1. The cumulative settlement of ZJ06 support reached 16.3 mm during the second step (the second section jacking completed), which was close to the limit value of 20 mm. In order to ensure the safety of the follow-up project, active compensation was carried out before the third Step (the second section completed the third section preparation adjustment). The lifting amount was controlled by 10 mm, and the cumulative settlement after lifting was about 5.6 mm. The stress state after compensation was good.

2. The cumulative settlement of ZJ07 support reached 13.9 mm during the fourth step (the third section jacking completed), which was close to the limit value of 20 mm. The cumulative settlement of ZJ06 support reached 9.7 mm during this period. Active compensation was carried out before the fifth step (the third section completed the fourth section preparation adjustment). The settlement compensation lifting of ZJ06 support was controlled by 5 mm, and the cumulative settlement was about 6.3 mm after lifting, and the compensation error was close to 1.6 mm. The settlement compensation amount of ZJ07 support is controlled by 10 mm, and the cumulative settlement is about 5.2 mm after lifting, and the compensation error is close to 1.3 mm.

By using the method of active compensation, the whole project avoids the problem of large settlement difference and excessive cumulative settlement, and ensures the stress safety in the process of jacking.

5.3 Support deformation analysis
In addition to vertical force, the support also bears horizontal force. The horizontal force of the whole steel truss bridge is the largest at ZJ02-1 support, and the tail torsion of the support is very obvious. In the jacking process, the maximum torsion occurs at 5 mm. Because the horizontal force is mainly produced by the lateral rectification and lateral limiting device in the jacking process, the horizontal force has little effect on the stability of the support structure and is artificially controllable. In the construction process, if the lateral deviation of the steel truss is too large or the unilateral stress concentration is in the process of lateral correction, there is also the risk of support overturning.
6. Conclusion
Based on the jacking construction of Pudong Canal Bridge on Longdong Avenue, this paper establishes a three-dimensional model to simulate the stress of the support and obtain the settlement value of a standard working condition. The random combination of settlement is used to simulate the support reaction force and steel pipe stress caused by support settlement in practical engineering, which provides a theoretical basis for support settlement compensation. Finally, the accuracy of theoretical research is verified by real engineering settlement monitoring and support compensation. The conclusions are as follows:
(1) In this paper, the random combination analysis method is used to obtain the settlement control index: uneven settlement is not more than 5 mm, and the maximum settlement is not more than 20 mm. This index can effectively guarantee the quality of the project.
(2) In the river-crossing stage, the stress increases sharply due to the decrease of the stress area caused by the suspension of the support, so the settlement increases sharply. In practical engineering, the settlement difference between adjacent supports is reduced by means of support settlement compensation, so as to ensure the safety of the support.
(3) The horizontal force generated by the Lateral correction and limiting device during the jacking process has little effect on the stability of the support structure, but there is still a risk of overturning, so the same attention needs to be paid to the horizontal force during the construction process to ensure the safety of the project.

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