Calculation and test on the construction support deformation for the viaduct of the subway Line 1 of Changzhou

Wang Weixing¹, Liu Teng², Pan Darong³*, Niu Longlong³, Dai Tianjiao³

¹Jiangsu Yanghu Construction Project Administration Co., Ltd, Changzhou, Jiangsu, 213157, China;
²Beijing Municipal Construction Group Co., Ltd, Beijing, 100045, China
³School of Architecture Engineering, Nanjing Institute of Technology, Nanjing, Jiangsu, 211167, China

*Corresponding author’s e-mail: pandarong@msn.com

Abstract: When the high formwork support collapses during construction, the bars present obvious deformations that exceed the normal limit. The deformation characteristics of the high formwork support were calculated and analyzed by nonlinear buckling finite element method, and the deformation test was carried out by using the automatic deformation monitoring system based on machine vision. The results show that the FE results are in good agreement with the tested results, and the FE calculation can predict the deformation behavior of the structure relatively well.

1. Introduction

In recent years, accidents of the bridge structures constructed with full space support have been frequently caused by the collapse of the supports. For example, in the construction of Yanba expressway approach bridge in Shenzhen, there was a large height error in the column, and no cross bracing in the lateral direction of the support, while the number of cross bracings in the longitudinal direction of the support is insufficient. All of these lead to the instability of the support body and the collapse of the beam body, causing that 69 people fell and 19 injured (with 5 seriously injured)[1]. In these accidents, the collapse of formwork support system with the height more than 8m (high formwork support) accounts for a very high proportion[2]. The main reason of the accidents is the overall instability of the supporting structure caused by human negligence, design defects, and construction problems[3-4]. In the construction process of the structure, due to the initial bending of the support members and other reasons, these unsteady support accidents, which are characterized by nonlinear instability, have infallible indications that the deformations of the members exceed the normal limits[5]. Therefore, the deformations of the high formwork support of the viaduct of Changzhou Metro Line 1 during the construction were calculated by nonlinear buckling finite element method, and the deformation characteristics of the whole structure at nonlinear buckling were studied in this paper. At the same time, an automatic deformation monitoring system based on machine vision was used to continuously monitor the deformations of the support at the construction site to verify the calculation and study results.

2. Structure situation

2.1 Main girder
The monitored structure under construction was a viaduct on Changzhou Metro Line 1. Its main girder was a 30 + 45 + 30m single-boxed and single-chambered continuous beam. The pier shaft was of 12.5m height, and the detailed sizes of this structure is shown in Fig. 1.

![Main structural drawing of the box girder](image1)

2.2 Support
Steel pipes with the diameter of 45mm were used as the support columns. Near the end diaphragm, in the range of 2.4m on the single side, the longitudinal and lateral spacing of the columns was 60cm × 60cm. Near the middle diaphragm, in the range of 2.7m on the single side, the longitudinal and lateral spacing of the columns was 30cm × 60cm, and in the range between 2.7m and 7.2m, that was 30cm × 60cm. Near the web position, the longitudinal and lateral spacing of the columns was set to 90cm × 60cm. At the hollow position, the longitudinal and lateral spacing of the columns was set to 90 cm × 90 cm. Near the flange position, the longitudinal and lateral spacing of the columns was set to 90cm × 90cm. The detailed arrangement of the support was shown in Fig. 2.

![Arrangement of the bridge support](image2)

3. Finite element analysis

3.1 Nonlinear buckling analysis theory
Nonlinear buckling analysis is more accurate than linear buckling analysis, so it can be used in the design or calculation of actual structures. This analysis method is to use a nonlinear static analysis technique which gradually increases the load to obtain the critical load when the structure becomes unstable. With the application of nonlinear technology, the model can contain the characters of initial defects, plasticity, gaps, large deformation responses, and so on. The nonlinear buckling caused by the initial bending
defects of the members is mainly considered in this paper.

3.2 Value of the initial bending defects

The Value of initial bending defects was taken from the statistical data of reference [6]. The initial bending rate = initial bending deflection / steel pipe length. The mean value of the initial bending rate was 2.4 ‰, and the standard deviation was 1.5 ‰, which obeyed normal distribution. When the finite element model was established, N sample parameters were randomly generated according to the above mean value and standard deviation, Where N was the total number of the members. Then, the N sample parameters were randomly assigned to each member, so that each member had an initial bending rate which obeyed the above mentioned statistical distribution. In addition, considering the randomness of the member bending direction in the actual structure, the bending direction angle was also set for each member randomly when the member model was established.

Finite element model of the structure

The general finite element software ANSYS was used for nonlinear buckling calculation. The Beam188 linear beam element was used to simulate the supporting members, the Solid185 solid element was used to simulate the main girder, and the Shell181 shell element was used to simulate the steel formworks. The arc length method was used to solve the mechanical equations considering geometric nonlinearity[7-10].

The structural loads mainly contained the structure self-weight, personnel and construction equipment load, load from vibrating concrete and horizontal wind load. The structure self-weight was taken as the actual value, personnel and construction equipment load was taken as 1.0kN/㎡, load from vibrating concrete was taken as 2.0kN/㎡, and the standard value of horizontal wind load was taken as 0.308kN/㎡ according to the design code[11].

The connections between the main girder formwork and the support members were simulated as hinge joints. The right angle fastener between the horizontal member and the vertical member was the semi-rigid connection between the rigid connection and the hinged connection, and was simulated as torsion spring. According to the literature[12], the influence of the torsional rigidity of qualified right angle fastener on buckling bearing capacity is relatively weak. Taking the intermediate value 22.9kN·m/rad of the torsional stiffness range[12] of the qualified fasteners as the torsional rigidity of the torsion spring. The finite element model of the structure is shown in Fig. 3.

![Finite element model of the structure](image)

3.3 Analysis on the finite element results

3.3.1 Lateral (X direction) deformation

The lateral (x direction) deformation of the support structure is shown in Fig. 4. As can be seen from the figure, the maximum lateral deformation of the structure is about 0.5 mm, approximately in the middle part of the support structure.

3.3.2 Vertical (Y direction) deformation

The vertical (Y direction) deformation of the support structure is shown in Figure 5. It can be seen from
the figure that the maximum vertical deformation of the structure is 2.6mm, which is approximately at the upper part of the support structure.

3.3.3 Longitudinal (Z direction) deformation
The longitudinal (Z direction) deformation of the support structure is shown in Fig. 6. As can be seen from the figure, the maximum longitudinal deformation of the structure is 9.3 mm, approximately at the upper part of the support structure.

4. Deformation monitoring experiment
For the high formwork support structure, it is difficult to work effectively for the traditional deformation monitoring method. If to dynamically monitor the deformations directly through displacement sensor, on the one hand, the installation position of the sensors could not be well solved; on the other hand, it would also cause interference to the construction process. To use total station to measure displacement had less interference to the construction process, but it cannot conduct dynamic monitoring. Indirect measurement of structural deformation information through acceleration sensor required twice integration, which would led to error accumulation[13]. Therefore, an automatic deformation monitoring system based on machine vision developed by the project team was used in this paper to test the real-time deformations of the support structure[14].

4.1 Test device
The hardware of the dynamic monitoring system included an image acquisition module, a data transmission and processing module, an LED light compensation module, a measurement target, and a monitoring system server. During the construction process, the image acquisition module automatically collected the real-time image of the measurement target on the support in the monitoring area. When the support deformed, the position of the observation point on the measurement target changed, the monitoring system automatically recognized the deformation observation point and then sent the data to the monitoring system server. When operating at night, the LED light compensation module was used for optical compensation to improve the recognition effect. The detail of the system is shown in Fig. 7.
4.2 Layout of the measured points
According to the finite element results and the in-field measurement conditions, the targets were set on the east side of the coping, namely the observation points D1 ~ D5 respectively, shown in Fig. 8.

Fig. 8 Measurement points of the bridge framework support

4.3 Test result analysis
The measure tracked the whole process of concrete pouring, from 18:00 to 02:10 in the next morning. Photos were taken every 30 minutes. The deformation curves of each observation point are shown in the following figures.

Fig. 9 Deformation curves of point D1

Fig. 10 Deformation curves of point D2

It can be seen from the deformation curves of D1 that the measured maximum vertical deformation is 2mm, and the maximum horizontal deformation is 8mm at the completion of pouring.

It can be seen from the deformation curves of D2 that the measured maximum vertical deformation is 3mm, and the maximum horizontal deformation is 4mm at the completion of pouring.

Fig. 11 Deformation curve of point D3

Fig. 12 Deformation curve of point D4
It can be seen from the deformation curves of D3 that the measured maximum vertical deformation is 62mm, and the maximum horizontal deformation is 8mm at the completion of pouring. It can be seen from the deformation curves of D4 that the measured maximum vertical deformation is 8.6mm, and the maximum horizontal deformation is 7.6mm at the completion of pouring.

![Deformation curve of the observation point D5](image)

Fig. 13 Deformation curve of the observation point D5

It can be seen from the deformation curves of D5 that the measured maximum vertical deformation is 6.2mm, and the maximum horizontal deformation is 5.0mm at the completion of pouring.

The calculated values of the observation point deformations were extracted and compared with the measured values, as shown in Tab. 1.

| Deformation          | D1(mm) | D2(mm) | D3(mm) | D4(mm) | D5(mm) |
|----------------------|--------|--------|--------|--------|--------|
| Calculated value Y   | 0.7    | 0.8    | 2.5    | 2.6    | 2.5    |
| Z direction (Longitudinal) | 2.4    | 2.5    | 6.8    | 6.9    | 6.7    |
| Measured value Y     | 2      | 3      | 62     | 8.6    | 6.2    |
| Z direction (Longitudinal) | 8      | 4      | 8      | 7.6    | 5.0    |

Tab. 1 Comparison between the calculated deformations of the observation points and the measured deformations

It can be seen from the table above that there are some deviations between the calculated values and the measured values due to the inaccuracy of the initial defects and the joint stiffnesses, and the regardless of the complicated factors in the finite element calculation. However, the calculated deformations of most measurement points are not much different from the measured values, basically in the same order of magnitude; the calculated deformation laws are relatively consistent with those gained by measure. This indicates that the calculation results have certain reference significance, and the finite element method can calculate the buckling possibility of this kind of structure. The calculation values of the observation point D3 are quite different from the measured values, this is because the D3 target was moved from the original position before the 16th measure. From the curves recorded by this system, the change is quite obvious. It indicates from another angle that the deformation monitoring system can respond automatically, and a system alarm event will be generated when the preset alarm value is reached.

5. Conclusion
Through the finite element calculation and monitoring test of the high formwork support deformation, it is found that the vertical deformation and horizontal deformation of the supporting structure of the viaduct of Changzhou Metro Line 1 are small, which do not exceed the design requirements, so the structure is safe. The differences between the calculation results and the test results are small, which verifies the correctness of the calculation method. The calculation method and results can provide reference for other similar bridge support construction, and have certain reference significance for the studies on high formwork support structure safety.
Acknowledgments
This work is Supported by Jiangsu construction system science and technology project (2017ZD131).

Reference
[1] http://www.chinanews.com/2000-11-28/26/58450.html
[2] Nan Xie, (2012)Renzhong Liang, Jingjing Wang. Occurrence of human errors in high falsework and influence on structural safety [J]. Engineering mechanics,29( Supplement I): 63-67.
[3] Tingsheng Zhao, Zehui Wang, Xianglin Gu. (2005)Statistical Parameters of the Formwork Supports [J]. Construction technology, 34(3): 49-52.
[4] Renzhong Liang, Nan Xie, (2010)The safety assessment analysis of supports for formwork in china [J]. Industrial safety and environmental protection, 36(8): 36-37.
[5] Xuexia Yuan, Weiliang Jin, Zheng Lu, Xin Liu, Tianmin Chen.(2006) A study on the stability bearing capacity of fastener – style tubular steel formwork-supports [J]. China civil engineering journal, 39(5):43-50.
[6] Nan Xie, Yong Wang, (2008)Study on load-carrying capacity of super high supports for formwork, 25( Supplement I): 148-153.
[7] Hongbo Liu, Qiuhong Zhao, (2010)Xiaodun Wang, et al. Experimental and analytical studies on the stability of structural steel tube and coupler scaffolds withoutX-bracing [J]. Engineering Structures, 32(4):1003-1015.
[8] NanXie, Xiaohui Fu, Lifeng Wang, Hang Hu, Tong Wu, (2016)Design method of load and resistance factor for high falsework with couplers [J]. Engineering mechanics, 33(10): 68-75.
[9] Tianxia Song, (1996)Finite element calculation of nonlinear structure [M]. Wuhan: Huazhong University of Technology Press.
[10] Ji Chen, (1994)Theory and application of steel structure stability [M].Beijing, Science and Technology Literature Press.
[11] JGJ130-2011, (2011)Safety technical code of construction fastener type steel pipe scaffold [S]. Beijing: China Building Industry Press.
[12] Yong Wang, Nan Xie, (2007)The influence of horizontal strengthened story and vertical diagonal bracing to fastener style bearing capacity of super high supports for formwork [J]. Architecture, (16): 36-37.
[13] Zhicheng Qiu. (2004)A new analysis method of Photogrammetry error [J] . Science of Surveying and Mapping, (3): 10-13 .
[14] Bing Yao, Qilin Zhao, Ting Rui, Yong Ding. (2009)Distance measurement method for non-contact detection of concrete bridge cracks [J]. China Municipal Engineering, (03):38-40.