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RESEARCH ARTICLE

CONSTRUCTION SAFETY INSPECTION PLATFORM OF HIGH-SPEED RAILWAY SUPER LARGE SWIVEL BRIDGE BASED ON NUMERICAL SIMULATION

Yongjun Zhang[a], Qiangqiang Ma[a,*], Tianhui Ma[b], Shengrong Xie[c], Jun Peng[d]

[a]College of Science, Qingdao University of Technology, Qingdao 266033, China
[b]State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China
[c]School of Energy and Mining Engineering, China University of Mining & Technology-Beijing, Beijing 100083, China
[d]Sinosteel Maanshan General Institute of Mining Research CO.,LTD, Maanshan 243000, China
**Corresponding Author E-mail: jackmqq@163.com-*

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ABSTRACT

In recent years, when building bridges across existing railways, in order to reduce the interference to the railway operation line during the construction process, parallel railways are often used to cast bridges and then rotate them. In this paper, combined with the engineering example of Zhaochuan Super Swivel Bridge on Beijing-Zhanghai High-speed Railway, the key and difficult points of the swivel bridge during construction are monitored, and compared with the computer simulation data, the static friction coefficient, dynamic friction coefficient and friction couple distance of the swivel system are obtained. Model each component of the bridge body, establish a safety monitoring and early warning method, system, storage medium, and early warning platform, and visually display the safety degree of components at different stages and locations by color discrimination.

KEYWORDS

swivel bridge; monitoring measurement; numerical simulation; visualization; early warning platform

1. INTRODUCTION

Bridge safety monitoring can be divided into two types: during construction and during operation. During the construction phase, necessary on-site monitoring is carried out under specified conditions to verify the correctness of design parameters and to modify the next construction plan (Francis & Griggs, 2011; Cao & Wang, 2011). During the operation period, monitoring is mainly conducted periodically for short-term or long-term effects such as train loads and natural environments to assess the service period health status of the bridge. The construction technology of the rotary bridge has become more mature, but monitoring systems for this specific bridge construction method during the construction period are still under development (Cheng & Zhang, 2011; Peng, 2013; Lei, 1998). For ordinary cast-in-place beam bridges, only necessary monitoring such as settlement, alignment, and prestressed tendon tension control is carried out, and it is recorded by on-site personnel using paper and pen, and then compared with paper-based drawings in the later stage, lacking a unified data upload and processing platform. Under the existing technical methods, the amount of data collected is limited by time and operational environment, and the data collection method is relatively primitive and simple. At the same time, the recorded data is easy to lose, and it is necessary to assign a dedicated person to enter the data to form an electronic file for preservation.

The existing monitoring technology for cast-in-place box girder bridges is relatively backward, with primitive and simple monitoring methods and a lack of systematic platform construction. For the construction of rotary bridges, special monitoring of the force at the ball and socket joint and the rotation of the bridge needs to be carried out on the basis of traditional monitoring, and BIM technology and comprehensive and advanced monitoring platforms should be used for unified management (Wang, 2015; William et al., 2013; Zheng, 2018).

2. PROJECT OVERVIEW

The Zhaochuan Elevated Bridge is a super rotary bridge on the Chongli section of the Beijing-Zhangjiakou high-speed railway, which is the transportation guarantee line for the 2022 Winter Olympics and a national key project for the construction of the Beijing-Tianjin-Hebei integration. The bridge is located between DK17+641.2 and DK25+495.21, with a center mileage of DK21+568.205 and a length of 7854.01m. It is a double-line super bridge that adopts the pier-top rotary technology. The bottom of the bridge is the existing Zhangtang Railway Chongli section, involving a section from DK24+950 to DK24+996, with a center mileage of DK24+972.8, forming a 68° angle with the super bridge of the Chongli section of the Beijing-Zhangjiakou high-speed railway, as shown in Figure 1 (Ma, 2018).

Figure 1: Rendering of Bridge

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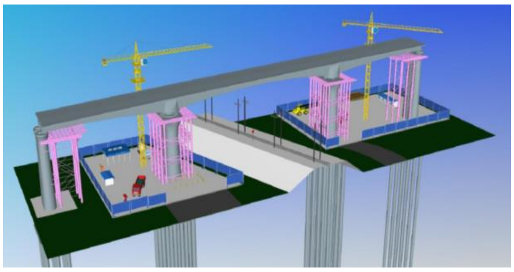


Figure 2: Schematic of Bridge

The bridge adopts a pier-top horizontal rotary process and is equipped with a pier-top rotary structure. After the construction of the main beam ends, the beam body is rotated counterclockwise by 68 degrees to the design position before the edge-span and middle-span closure is carried out. The construction period of this rotary box girder bridge is about 2 years, including one winter. The rotary bridge section of the bridge is a continuous curved beam bridge with a length of 40+64+40m, as shown in Figure 2. The radius of the horizontal curve is R=3500m, the radius of the vertical curve is 20000m, and the distance between the dual-track bridge lines is 4.6037m. The main span intersects with the Zhangtang Railway at DK24+972.8, with a crossing angle of 68 degrees. This continuous beam section adopts a pile foundation with a circular end solid pier and a variable cross-section single-box single-type continuous box girder structure, and the construction process is the hanging basket cantilever pouring method + rotary construction. The bridge is cantilevered on both sides of the parallel Zhangtang Railway, with two 62-meter-long cast-in-place beam bodies, totaling 18 segments. At the rotary bridge pier of the curved beam bridge, a pier-top horizontal rotary process is used, and a pier-top rotary structure is set up. After the construction of both ends is completed, the beam body is rotated counterclockwise by 68 degrees to the design position for the edge-span and middle-span closure.

3. MONITORING AND EARLY WARNING BASED ON NUMERICAL SIMULATION

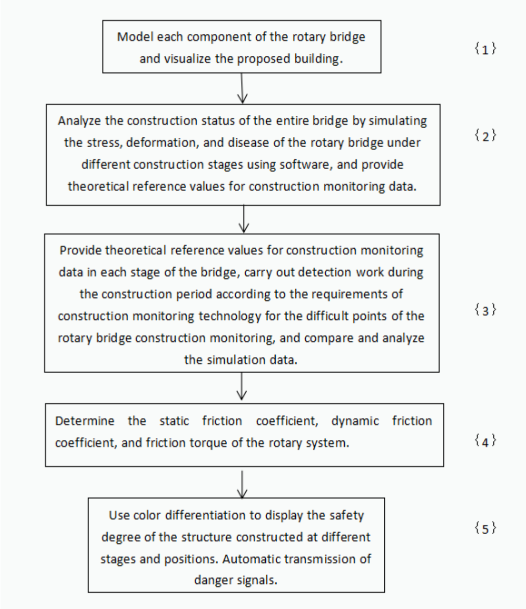
Based on the safety monitoring and early warning plan proposed for the super bridge on the Chongli section of the Beijing-Zhangjiakou high-speed railway, the plan features dividing the safety early warning plan for rotary bridges into five steps, As shown in Table 1.

Model each component of the rotary bridge and visualize the proposed building.

Analyze the construction status of the entire bridge by simulating the stress, deformation, and disease of the rotary bridge under different construction stages using software, and provide theoretical reference values for construction monitoring data.

Provide theoretical reference values for construction monitoring data in each stage of the bridge, carry out detection work during the construction period according to the requirements of construction monitoring technology for the difficult points of the rotary bridge construction monitoring, and compare and analyze the simulation data.

Table 1: Steps of Safety Early Warning Plan



Model each component of the rotary bridge and visualize the proposed building. {1}

Analyze the construction status of the entire bridge by simulating the stress, deformation, and disease of the rotary bridge under different construction stages using software, and provide theoretical reference values for construction monitoring data. {2}

Provide theoretical reference values for construction monitoring data in each stage of the bridge, carry out detection work during the construction period according to the requirements of construction monitoring technology for the difficult points of the rotary bridge construction monitoring, and compare and analyze the simulation data. {3}

Determine the static friction coefficient, dynamic friction coefficient, and friction torque of the rotary system. {4}

Use color differentiation to display the safety degree of the structure constructed at different stages and positions. Automatic transmission of danger signals. {5}

Determine the static friction coefficient, dynamic friction coefficient, and friction torque of the rotary system.

Use color differentiation to display the safety degree of the structure constructed at different stages and positions. Automatic transmission of danger signals.

3.1 Bridge Visualization Modeling

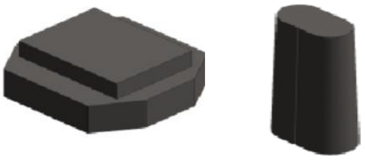
Based on BIM technology, each component of the rotary bridge is modeled and the proposed railway is visualized. The modeling was carried out using Autodesk Revit 2017 software, and the bridge pile foundation, pier body, pier cap, bridge body, rotary model, internal reinforcement, and surrounding facilities were modeled separately. Finally, they were overlaid to form the entire bridge model, as shown in Figure 3 & 4.

3.2 Numerical Simulation of Construction Stage

By simulating the stress and deformation of the rotary bridge under different construction stages using computer software, and analyzing the construction status of the entire bridge during the construction period, simulated reference values for construction monitoring data are provided.

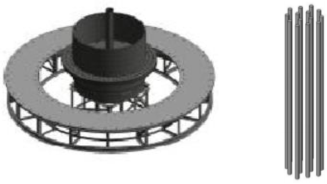
Specifically, the numerical simulation of the rotary bridge under different construction stages includes:(1) Analysis of the stress and deformation of the entire bridge during the construction period of the rotary bridge. A numerical model of the bridge's overall structure was established using Midas/Civil finite element software, taking into account the material properties of the concrete, steel strands, and support conditions during and after construction, as well as the calculation of construction stages. The data on changes in the internal forces, stresses, and deformations of the rotary bridge structure during the entire construction process were obtained. (2) Analysis of the stress and deformation of the ball-and-socket steel structure. A detailed model of the ball-and-socket was created using ANSYS Workbench. Under different construction conditions, the internal force results of the cantilever root calculated by MIDAS were extracted and set as the load on the two end faces of the intermediate support beam section in the ball-and-socket model. The stress and the distribution of the

main concrete stress at the pier cap were calculated. The theoretical value of the traction force of the ball-and-socket rotation under different friction coefficient groups was calculated. (3) Analysis of the settlement of the bridge piers during the construction process of the entire rotary bridge. A pile-soil model was established using FLAC3D, taking the total weight of the components above the abutment as the load condition for the model under different construction stages. The settlement of the bridge structure under vertical load, the lateral friction resistance between the pile body and the soil, and the distribution of pile axial force were calculated. (4) Analysis of the internal temperature of concrete during winter construction. ABAQUS software was used to establish a numerical model of the bridge box girder section with different cross-sections at different times. The outdoor environment and internal chamber temperature data collected by on-site temperature sensors were used as the boundary conditions for software simulation to calculate the internal temperature of the concrete in the box girder section during winter construction.



a. Abutment b. Pier Column

c. Pier Cap d. Main Beam



e. Rotary Structure f. Foundation Pile

Figure 3: BIM models of various components of the bridge

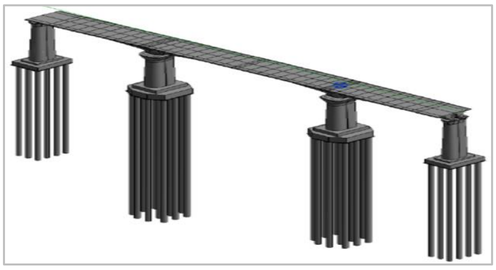


Figure 4: Overall bridge model

3.2 Numerical Simulation of Construction Stage

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3.3 Numerical Simulation and Comparison Analysis with Theoretical Data

The theoretical reference values for construction monitoring data in each stage of the bridge were used to carry out monitoring work during the construction period according to the requirements of construction monitoring technology and the key difficulties of rotary bridge construction monitoring. The monitoring data were compared and analyzed with the simulation data.

The main analysis contents include:(1) Pre-stressing reinforcement tensioning, number of tensioning forces, and data during the cantilever pouring stage of the bridge. (2) The buried strain sensors of characteristic sections during the construction process of the rotary bridge were used to collect strain data under different construction stages and conditions, and the internal force values of the sections were calculated using formulas. (3) Horizontal and vertical strain sensors were buried directly below the lower ball-and-socket, and data was collected. (4) Settlement monitoring points were installed 1m above the bottom surface of the bridge pier of the rotary bridge, and six monitoring points were set up within the monitoring plane to collect settlement data. (5) Vertical displacement meters were installed at each support foot. The displacement meter was fixed vertically to the steel support foot with a suction cup, and the pointer pointed to the slide rail. During the rotation process, the displacement meter followed the support foot to move, and the slight vertical displacement change

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caused by the vertical pointer during the movement was collected to determine the inclination angle of the bridge ball-and-socket and upper main beam structure. (6) Traction force of the traction device was collected during the 5° trial rotation and formal rotation process.

3.4 Parameter Solution of the Rotary System

The important system parameters for safety monitoring of the rotary bridge include the static friction coefficient, dynamic friction coefficient, and friction torque distance of the special system, and the data during the special process needs to be collected and analyzed during the simulation process.

Firstly, the BIM model and sensor model are imported into the safety warning cloud platform. Through spatial positioning, the position of the strain gauge monitoring point is located in the BIM model in three-dimensional space. Then, the numerical simulation data and corresponding on-site monitoring data are imported into the cloud platform and associated with the collected sensor positions. At the same time, the on-site monitoring point picture is saved as a texture in the sensor model attribute, realizing the comparison and reference of the model monitoring point position and on-site photo.

Comparative curve diagrams of actual measurement data and simulation data are generated with the horizontal axis as the construction condition time and the vertical axis as the measurement value. For the stress of the main beam characteristic section, the stress of the pier cap ball-and-socket, and the bridge pier settlement data, the average value, variance, and standard deviation of the actual measurement and simulation data are compared, and the maximum value of the actual measurement data is compared with the standard value. A temperature distribution curve of the concrete section of the box girder bridge is generated with the horizontal axis as the time at different times of the day and the vertical axis as the temperature measurement value. The power exponential function fitting method is used to obtain the temperature gradient distribution inside the concrete and the temperature judgment conditions for grouting in the prestressed pipeline during winter. A vertical displacement curve of different support foot displacement meters during the rotation process is generated with the horizontal axis as the different angles during the rotation process and the vertical axis as the vertical displacement amount. The vertical displacement change law at the ball-and-socket position is observed to determine whether there is obvious inclination of the upper ball-and-socket and main beam.

Finally, through the comparison of the traction force of the traction device during the trial and formal rotation and the comparison of the rotation force under different friction coefficient conditions during numerical simulation, the static friction coefficient, dynamic friction coefficient, and friction torque distance of the rotary system are obtained.

3.5 Characterization of Danger Signals

During the monitoring and warning process, when a danger signal appears, it will be displayed with color differentiation according to the safety degree of components at different stages and positions. At the same time, the danger signal will be automatically transmitted to the warning platform, which is the final step of this system.

For stress and temperature data, 70% of the standard value data is taken as the red danger threshold, 50-70% is the orange warning threshold, and below 50% is the green safety range. For settlement data, 70% of the standard value data is taken as the red danger threshold, 50-70% is the orange warning threshold, and below 50% is the green safety range. For the traction force of the traction device, the theoretical solution of the traction force calculated based on the static and dynamic friction coefficients specified in the drawings fluctuates up and down by 15% as the green safety range; exceeding the theoretical solution by 15-30% is the orange warning range, and greater than 30% is the red warning range for traction force. For the inclination angle of the upper ball-and-socket and main beam during the rotation process, 50-75% is the orange warning range, and when it exceeds 75%, the support will stop rotating.

3.6 Platform Flowchart

The platform process is shown in Figure 5.

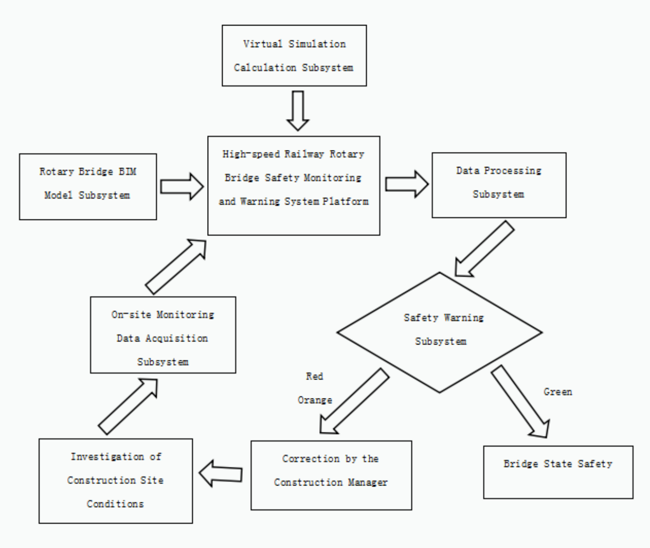

Figure 5: Detection Platform Flowchart

4. Warning Platform System

4.1 Establishment of the System Platform

The establishment of the system is based on MATLAB software.

In the first step, computer simulation data is exported. For Midas/Civil, ANSYS, and Flac3D software, the output position unit and node are picked through command flow or menu bar to determine the data selection location. The data is then exported as a ".txt" or ".xls" data document using the respective software's data export command.

In the second step, monitoring data is exported using an intelligent collection box connected to buried sensors which automatically collect data. The data is uploaded to the cloud for storage and can be exported in ".xls" format using a USB data cable connected to a microcomputer.

In the third step, MATLAB software is used to obtain data images. The software data path is set, and subfolders are established to classify and save the different data documents in the specified path. For example, for settlement data, the simulated, monitored, and standardized data are placed in their respective subfolders. The "num=xlsread(filename)" command is used in MATLAB to import the data, and the "plot(X,Y,LineSpec)" command is used to draw the graph.

In the fourth step, data feature value processing is carried out. Data processing and analysis can be performed using the software's menu command or custom functions. Common mathematical statistical calculation functions include:

1）max(x,dim): find the maximum element;

2）min(x,dim): find the minimum element;

3）mean(x,dim): calculate the average value;

4）std(x,flag): calculate the standard deviation, where flag is the selected method of standard deviation calculation;

5）prod/cumsum(x,dim): calculate the sum/cumulative sum;

6）cov(x): calculate the covariance matrix;

7）cov(x,y): calculate the correlation matrix.

The parameter "dim" represents the dimension.

In the fifth step, data analysis is performed. Based on the graphs and data obtained from the previous steps, it can be determined whether the data contains any abnormal situations. If the trend and characteristics of the simulated and measured data are consistent, and there are no abnormal or sudden changes in the mathematical and statistical features, it indicates that the simulated and measured results have a high degree of fit, the data is authentic and effective, and the bridge is in a healthy state. If the trend and characteristics of the simulated and measured data are different, and there are significant differences in the mathematical and statistical features, the computer model parameters used for simulation should be checked and adjusted first to identify any software or program calculation problems. Based on the on-site construction work, the program parameters should be adjusted in a timely manner until the results are correct and meet the specified limits. The model can then be used as a reference guide for various steps in the construction process and for subsequent warning work.

4.2 Application of the System

Simulated data can be exported in the post-processing stage of program calculation by selecting appropriate elements and nodes. Collected data can be saved on the terminal, uploaded to the cloud, downloaded and exported using data acquisition instruments. MATLAB software can be used to compare the two types of exported data and generate graphs. In the software, the maximum value, minimum value, expectation, mean square deviation, and covariance can be calculated using the built-in functions in the drawing software to determine whether there are any abnormal situations in the data. If the trend and characteristics of the simulated and measured data are consistent, and there are no abnormal or sudden changes in the mathematical and statistical features, it indicates that the simulated and measured results have a high degree of fit, the data is authentic and effective, and the bridge is in a healthy state. If the trend and characteristics of the simulated and measured data are different, and there are significant differences in the mathematical and statistical features, the computer model parameters used for simulation should be checked and adjusted first, followed by a check of the on-site monitoring procedures and steps to identify the problem, as shown in Figure 6.

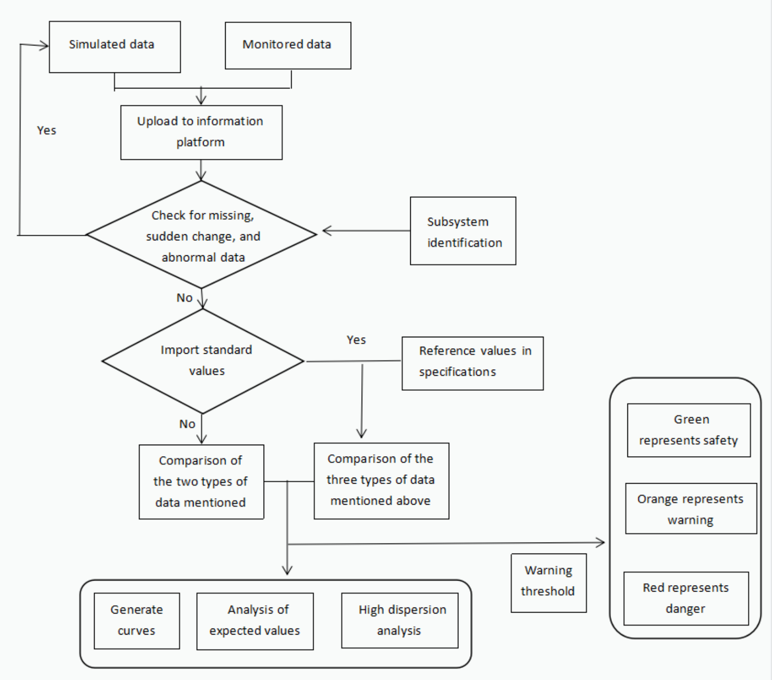

Figure 6: Application Process

5. CONCLUSION

The measurement and monitoring technology of the rotating bridge is an important link to ensure that the rotating bridge is smoothly positioned. Real-time measurement and monitoring of data and equipment during the rotation process can reduce danger and sacrifice. Adjusting the beam posture in a timely manner according to the measured data greatly improves the accuracy of the rotation positioning.

This platform has created an intelligent monitoring and construction method, which keeps all monitoring information in electronic form and uploads it to the cloud for timely viewing and feedback. At the same time, by mastering multiple sources of information through various monitoring methods, the safety status of the rotating bridge construction stage can be better judged, problems can be found and timely warning and resolution can be processed to ensure construction safety.

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