Deformation Monitoring Analysis of Kilometer-Scale Bridge in Mountain Canyon - A Case Study of Kaizhou Lake Bridge

Zongyuan Ma[1*], Chenglong Xiang[1], Dejun Zhou[1], Zhijiang Fang [2], Siyang Yu[2]

[1]Guizhou Communications Polytechnic, Guiyang 551400, China
[2]Guizhou Communications Construction Group Co., LTD., Guiyang 550002, China)

*Correspondence: mzy_gogo@sohu.com

Abstract. The complex and variable mountainous canyon environment has a significant impact on the operation of highway bridges. Taking the health monitoring of the Kaizhou Lake largescale bridge on the Weng'an-Kaiyang Expressway in Guizhou Province, China as an example, this paper analyzes the structural deformation regularity· of a kilometer-scale bridge in a mountainous canyon under the influence of wind environment changes within one year. It is found that the deformation and displacement of the main structures, such as the main beam and cable tower of the bridge, are larger in spring and winter when the temperature is low, but the overall deformation is within the controllable range, and the operation of the bridge is in good condition. Long and large suspension bridges are generally suitable for the transportation requirements of mountainous canyon areas.

Keywords: Mountainous canyon, Largescale bridge, Health monitoring, Deflection, Displacement.

1 Introduction

Guizhou is the province with the largest area of Karst of China and the highest proportion of mountainous area, with the whole region dominated by alpine and gorge terrain. Bridges have become the key nodes for paving a smooth highway network between mountains and gorges [1]. Currently, nearly 30,000 bridges have been built or are under construction, covering almost all bridge types in the world today. Nearly half of the world's top 100 mountainous high bridges are in Guizhou, earning it the title of "Bridge Museum". As key nodes in the mountainous highway network, bridges use information technology to strengthen health monitoring of bridge structures, which is of great significance for preventing and resolving major safety risks in the operation of long and large highway bridges and ensuring the safety and durability of bridges [2,3]. This article takes the health monitoring of the Kaizhou Lake Extra-large Bridge on the Weng'an-Kaiyang Expressway in Guizhou Province, China as an example, analyzing the monitoring results and patterns of structural deformation of kilometer- scale high

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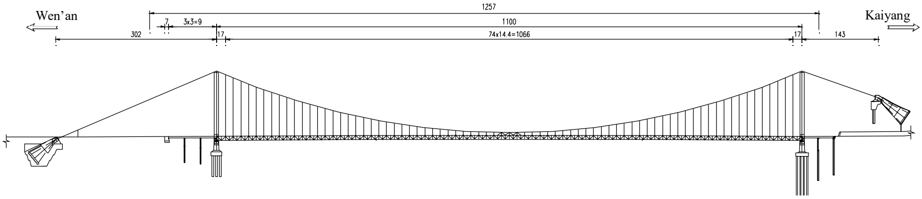
bridges in mountainous gorges over one year, providing a reference for related projects.

2 Engineering Background

The Weng'an-Kaiyang Expressway starts from the Baixi interchange in Weng'an County, Guizhou, connecting the existing Guiyang-Weng'an Expressway and the expansion project of the Zunyi-Guiyang section of the Lanhai National Expressway. The total length of the route is 48.732 kilometers, with a bridge-tunnel ratio of 42.72%. In addition, two interconnected connecting lines are built, totaling 1.896 kilometers. The Kaizhou Lake Bridge is located on the K35-K37 section of the Weng'an-Kaiyang Expressway, spanning the Luowang River Canyon. The bridge has a two-way four-lane road (each lane is 3.75 meters wide), with a design speed of 80 kilometers per hour and a bridge deck width of 24.5 meters. The main bridge of the Kaizhou Lake Bridge is a 1,100-meter single-span steel truss suspension bridge with main cable side spans of 302 meters and 143 meters respectively; the main cable mid-span is 1,100 meters with a vertical span ratio of 1/10; the main towers are 139.0 meters and 141.0 meters high respectively. The approach span on the Weng'an side is widened in the area connected to the interchange and uses cast-in-place box girders, while the approach span on the Kaiyang side uses simply supported and laterally continuous T-beams. The center pile number of the main bridge is K36+075, and the total length of the bridge is 1,257 meters. The main beam uses a steel truss stiffened beam with a plate-truss composite structure; the main tower body uses a reinforced concrete thin-walled hollow portal frame structure; the main cable uses prefabricated parallel steel wire strands; the Weng'an side uses gravity anchors, and the Kaiyang side uses tunnel anchors. The section and photos of Kaizhou Lake bridge are shown in Figure 1.



(a) Bridge vertical section (unit: m)

(b) On-site photos

Fig. 1. Section of Kaizhou Lake bridge and its on-site photos

2.1 Bridge Structure Form

The main beam is a steel truss stiffened beam with a plate-truss composite structure, consisting of the main truss, cross beams, bridge deck, and lower horizontal braces. The main truss is a Warren-type truss with vertical rods, connected to the main cable via slings. The cross beams are truss-style structures, equidistant in height with the main truss, and the lower horizontal braces are arranged in a K-shape. The bridge deck is made of orthotropic steel deck plates, composed of top deck plates, longitudinal beams, cross beams, and longitudinal ribs (U-ribs and plate ribs). The main towers on both banks are of portal frame structure. The main tower on the Weng'an side stands at 139 meters high, while the one on the Kaiyang side is 141 meters high. The Weng'an side uses gravity anchors, while the Kaiyang side uses tunnel anchors. Both anchorage foundations utilize moderately weathered rock layers as the foundation bearing stratum. The cross-section of main beam for Kaizhou Lake bridge is shown in Figure 2.

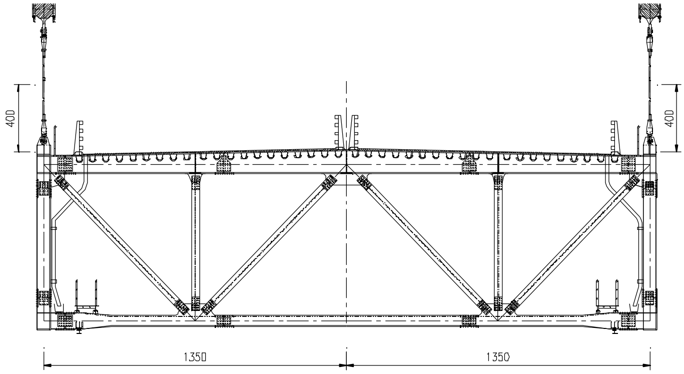


Fig. 2. Cross-section of bridge main beam (unit: cm)

2.2 Monitoring System

In March 2022, the health monitoring system of the Kaizhou Lake bridge implemented long-term online monitoring of key structural parts of the main bridge. The monitoring content mainly includes: bridge site environment, traffic status, deformation, structural force, and dynamic response. The system is divided into five subsystems according to functional levels: structural monitoring subsystem, traffic monitoring subsystem, data storage management subsystem, early warning evaluation subsystem, and user interface subsystem [4,5]. A total of 232 measuring points were installed on the whole bridge. According to the characteristics of the bridge site environment, driving environment, and structural form of the project bridge, the content of health monitoring during the operation period includes the following parts [6,7]:

(1) Load source and traffic monitoring: Natural environment monitoring at bridge site: wind load (including wind speed and direction), atmospheric temperature and relative humidity (including inside of anchor chamber), earthquake. Traffic load: Information about vehicles passing on the bridge deck, including speed, axle load,

information about overweight vehicles, traffic volume, etc. Structural temperature monitoring: Temperature field distribution of key sections.

(2) Structural response: Deformation monitoring: spatial deformation of the main tower; deflection of the control section of the main beam; displacement of the movable support; spatial deformation of the main tower and rotation of the main beam; displacement monitoring of the cable clamp. Cable force monitoring: monitoring the changes in cable force of the main cable strands and typical slings. Stress monitoring: monitoring the stress of the main beam control section and the fatigue damage performance of the local components. Structural vibration monitoring: vertical and lateral vibration characteristics of the main beam.

Table 1. Health monitoring system monitoring content table

Monitoring type	**Monitoring items**		**Sensor type**	**Measurement points**	**Threshold control**
Load source and traffic monitoring	Natural environment monitoring at bridge site	Wind load	Wind speed and direction indicator	4	√
Structural response monitoring	Deformation monitoring	Space deformation of the main tower	GNSS	5	√
		Deflection of control section of main beam	Deflection meter	16	√
		displacement of movable support	Displacement sensor	4	√
		Main beam smoothness monitoring	Noise sensor	1	
		Main beam smoothness monitoring	Noise sensor	4	√
		Rope clamp slip	Cable clamp displacement meter	16	√
	Cable force monitoring	Sling force	Soli sensor	16	√
		Cable tension	Soli sensor	20	√
	Stress monitoring	Stress and local fatigue damage performance of the main beam control section	Strain sensor	48	√
	Structural vibration monitoring	Vertical and transverse vibration characteristics of the main beam	Vibration sensor	21	√
Video monitoring	Bridge traffic monitoring		High-definition camera	6	
	Monitoring of support seat displacement status		High-definition camera	2	
	Anchor room security monitoring		High-definition camera	4	
Total				232	

3 Bridge Beam Deformation Monitoring Results

3.1 Bridge Site Wind Field

The annual wind speed on the bridge deck in 2023 is shown in Figure 3. It can be seen that the minimum daily average wind speed during the analysis period, the maximum daily average wind speed was 7.76m/s, both of which did not reach the red warning value; the predominant wind direction for the bridge was north.

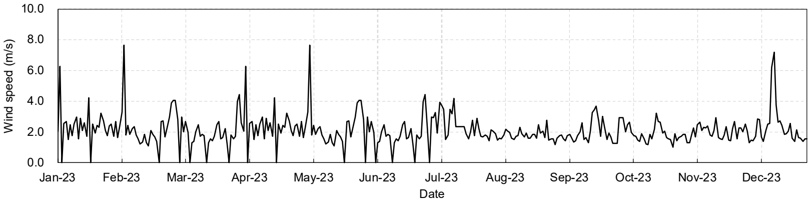
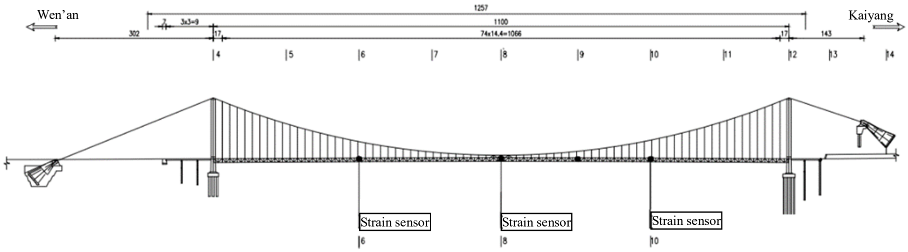
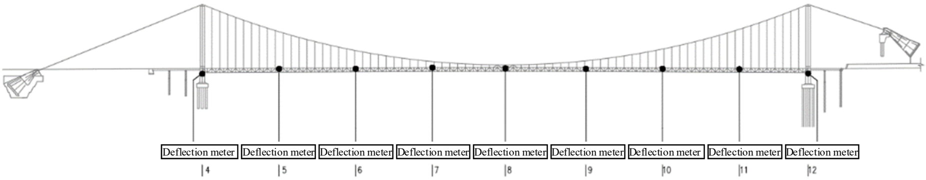


Fig. 3. Diagram of daily average wind speed variation in the bridge site area in 2023

3.2 Deformation of Main Beam Steel Structure



(a) Profile of measuring points layout



(b) Deflection measuring point of main beam

Fig. 4. Layout of strain and deflection measuring points for main beam structure

The strain of the main beam steel structure of the Kaizhou Lake Extra-large Bridge is mainly distributed at three sections of the four equal points of the main beam, with 16 measuring points on each section, totaling 48 measuring points. The arrangement of strain monitoring points is shown in Figure 4a. The arrangement of deflection measuring points of the main beam is shown in Figure 4b, which are located at the upstream and downstream of the steel beam section of the main beam. The deflection time history of the main beam in 2023 is shown in Figure 5. The deflection trend of each span of the main beam under live load is relatively stable, with a maximum deflection of -648.19mm; the alignment of the main beam is significantly affected by temperature.

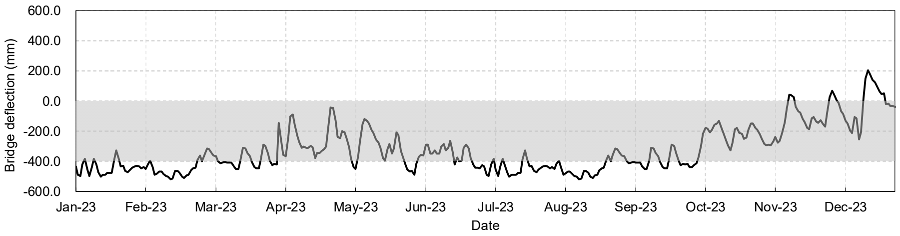


Fig. 5. Time-history diagram of main beam deflection

3.3 Main Tower Deformed

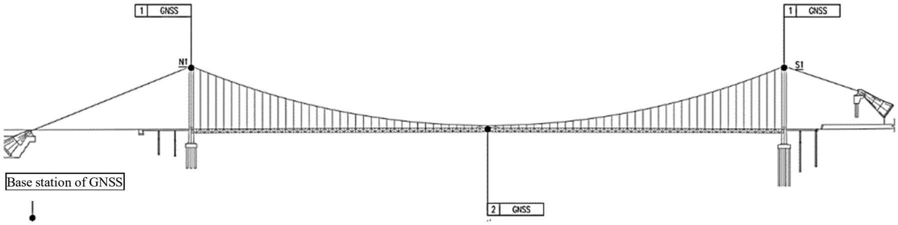


Fig. 6. GNSS measuring points for main tower displacement

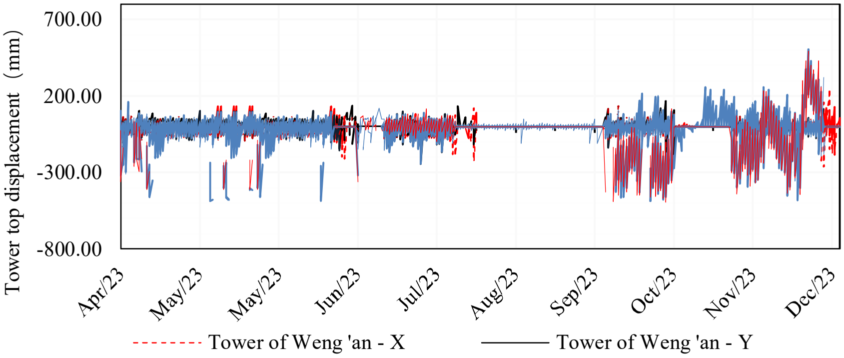


Fig. 7. Time-history diagram of spatial displacement of the main tower

The GNSS monitoring points for the main tower deformation are arranged as shown in Figure 6, located at the quarter points of the main span [8]. The time-history curve of the spatial displacement of the main tower in 2023 is shown in the Figure 7. The displacement trends of the main towers on both sides under the effects of temperature and live load are relatively stable. The maximum displacement of the Weng'an main tower in the longitudinal direction (x-direction) is -65.65mm, and the minimum is -211.36mm. The maximum displacement of the Kaiyang side main tower in the longitudinal direction (x-direction) is 135.59mm, and the minimum is -144.33mm. Compared with the upper and lower limits of the threshold calculated by the finite element method for the bridge structure, the spatial displacement of the main tower in all directions meets the requirements, and the overall stability of the bridge main tower structure is ensured [9,10].

3.4 Tower Support Deformation

The layout of the displacement monitoring points for the tower support is shown in Figure 8, which are symmetrically arranged on the main towers on the south and north banks of the river. The daily variation trend of the bearing displacement from January to December 2023 is shown in Figure 9 below. Under the effects of traffic load and temperature load, the characteristic values of the bearing displacement at measuring point are as follows: the maximum bearing displacement is 406.61 mm, and the minimum displacement is 406.61 mm. The bearing displacement is mainly affected by temperature, and the displacement trends of the upstream and downstream bearings on the same side remain consistent, with small differences in displacement between them [11-13].

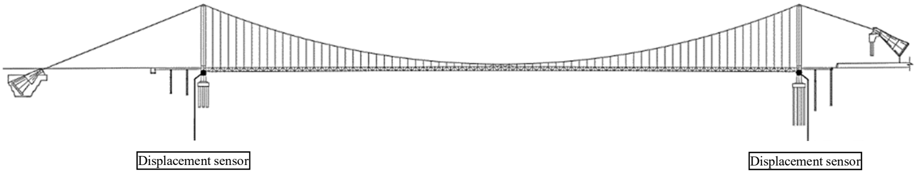


Fig. 8. Placement of tower support displacement monitoring points

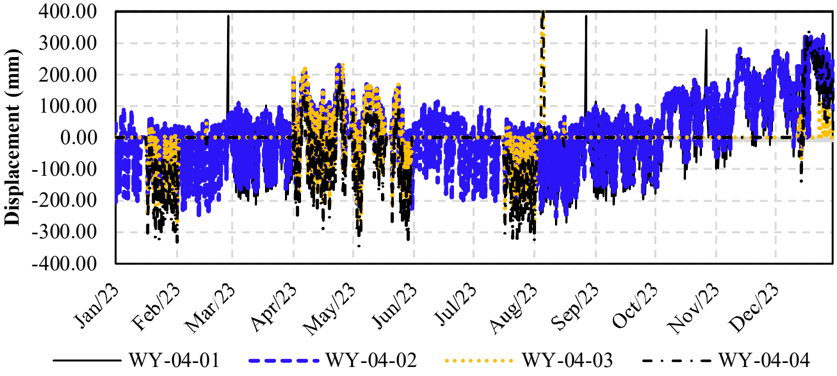


Fig. 9. Time-history diagram of tower support displacement

4 Conclusion

The deformation monitoring data of the main beam, main tower and supports of the Kaizhou Lake Bridge for the whole year of 2023 were analyzed, and the conclusions are as follows. The wind field in the gorge has a significant impact on the deformation and displacement of the main structure of the bridge, especially after winter when the temperature drops, causing the main beam of the bridge to shrink and produce an upward arch deformation (negative deflection), resulting in significant deformation and displacement of the main beam of the bridge. However, the overall deformation is within control. The values of deformation monitoring indicators for the main beam, main tower, and bearing of the bridge are all within the safety limit, and the bridge is operating normally with a safe and stable structure. In the future, the monitoring results of temperature, humidity, and vehicle traffic will be combined to analyze the coupling of multiple environmental factors and the response of the bridge structure during vehicle passing periods, as well as the response of the bridge structure.

Acknowledgments

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