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Analysis of Detection and Monitoring Technology in the Construction and Maintenance of Large Bridges

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Abstract: Currently, there is significant attention placed on the construction, management, and maintenance of large service bridges. Within the realm of bridge maintenance management, the utilization of detection and monitoring technology is indispensable. By employing these technologies, we can effectively identify any structural defects within the bridge, promptly uncover unknown risks, proactively establish maintenance strategies, and prevent the rapid deterioration of bridge conditions. This article aims to explore the advantages of applying bridge monitoring and testing technology and to discuss various methods for implementing detection and monitoring technology throughout the construction, management, and maintenance phases of large bridges. Ultimately, this will contribute to ensuring the safe operation of large bridges.

Keywords: Large bridges; Construction; Maintenance; Monitoring technology; Detection technology

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1. Introduction

The daily use frequency of large bridges is high, coupled with greater traffic pressure, affected by bad weather, structural aging, traffic accidents, and other factors, the health status of the bridge itself continues to decline. In the process of bridge management, it is necessary to use technical means to analyze the status of the bridge, take maintenance measures, extend the service life of the bridge, and provide technical support for the smooth construction and maintenance of large bridges.

2. Importance of inspection and monitoring technology in the construction, management, and maintenance of large bridges

2.1. Preventing defects

In China, the prevalence of large bridges is notable. Typically, during the construction, maintenance, and management phases of these structures, condition monitoring systems are commonly installed. Bridge management is accorded considerable importance to promptly identify existing bridge issues and implement targeted maintenance or reinforcement measures. Throughout the construction, management, and maintenance processes, employing technical methods to detect or monitor bridge structures and conditions enables the swift identification of concrete cracks, exposed reinforcement, water leakage from bearings, structural settlement, and other issues. This proactive approach helps prevent these problems from impacting the structural integrity of bridges and allows for timely interventions to address them. Ultimately, this contributes to enhancing the quality of bridge construction, management, and maintenance.

2.2. Scientific selection of conservation measures

With the rapid evolution of the transportation industry, the landscape of bridge construction has grown more intricate, giving rise to various types of structural issues that pose significant threats to safety. Leveraging detection technology and monitoring methods enables a comprehensive analysis not only of the bridge structure's appearance but also of the stability of its components, the distribution of problem areas, material performance, and structural damage. For instance, quasi-detection technology facilitates the analysis of issues like bridge protective layer thickness, extent of steel corrosion, and crack width, aiding in structural reinforcement efforts and extending bridge service life upon identifying root causes. Moreover, the application of detection technology supports bridge operation and management, facilitating the formulation of management and maintenance plans and the efficient allocation of management resources [1].

3. Application of detection and monitoring technology in the construction and maintenance of large bridges

3.1. Application of detection technology

(1) Manual detection

As the name suggests, manual inspection involves the direct observation of large bridges using testing equipment or the naked eye. Inspectors assess various factors such as protective layer thickness, crack location and depth, and steel corrosion, recording their findings based on field detection information. Manual inspection represents a traditional approach to bridge inspection. Given that some large bridges span valleys or rivers, inspection procedures may require platforms and scaffolding to facilitate access to appropriate positions on the bridge. While manual detection methods are straightforward, they come with certain drawbacks: the need for auxiliary equipment, considerations for personnel safety, relatively low detection efficiency, and susceptibility to subjective factors influencing test results. Nonetheless, despite the potential for errors, manual inspection remains a simple operation. Experienced engineers can often assess the overall condition of a bridge through visual inspection alone. This method is typically used for qualitative analysis and may serve as a supplementary approach to bridge detection.

(2) Non-destructive testing

Non-destructive testing technology enables the assessment of a bridge's structural performance and degree of deterioration without causing harm to its structure. Commonly used methods include image video, impact elastic wave, and ultrasonic wave testing. Image video testing utilizes tools such as vidicons and cameras, along with techniques like X-ray and infrared imaging, to gather information about the concrete material on the bridge's surface. Collected images are processed on a computer, segmented, and stitched together to form color-rich or high-resolution images. Detection algorithms are then employed to calculate information about bridge defects, offering high accuracy and efficiency. Impact elastic wave detection involves mechanically inducing impacts on materials, causing elastic waves to propagate through bridge components. When these waves encounter cracks or voids, they reflect, allowing inspectors to assess the internal state of the bridge based on waveform characteristics. While this method exhibits fast wave attenuation, its accuracy may require improvement, making it suitable for inspecting the quality of bridge steel components. Ultrasonic testing entails emitting ultrasonic waves into the concrete structure of the bridge and analyzing their propagation speed, time, and amplitude data to identify defects and their locations. This technology offers convenient on-site operation, easy equipment transportation, and strong penetration capabilities, allowing for comprehensive inspections of large bridge structures. Moreover, ultrasonic detection yields highly accurate results, capable of detecting and pinpointing even small defects [2].

Considering the strengths and limitations outlined for non-destructive testing technology, each method offers distinct advantages for bridge inspection. The image detection method excels in capturing comprehensive images of bridge structures in a single scan, boasting high efficiency in storing detection information. This makes it particularly suitable for identifying surface-level issues like holes or cracks on bridges. The elastic wave method, on the other hand, proves effective for probing internal defects within large concrete bridge structures. Its capability to penetrate deep into the structure makes it ideal for detecting hidden flaws. Lastly, the ultrasonic method is well-suited for conducting holistic inspections of bridge components.

(3) Sensor detection

Sensor detection involves installing sensors inside or on the surface of large bridges to monitor their condition using load testing methods and evaluate the results. Sensors represent a novel technology capable of transmitting real-time bridge information. However, it’s important to note that sensor testing can incur high equipment costs, and there’s a risk of damaging large bridges during the loading process, particularly those with long service lives. Moreover, environmental factors can affect sensor accuracy. To address these challenges, optical fiber sensors offer a viable solution. By embedding optical fibers within bridge structures, any deformation in the material causes a corresponding change in transmitted light waves. This enables real-time monitoring of deformation, stress, and cracks in the bridge structure. Optical fiber sensors are lightweight, compact, and resistant to electromagnetic interference, ensuring sensitive and accurate detection without being influenced by changes in force. Therefore, different types of sensors can be selected based on the specific requirements of bridge inspections.

3.2. Application of monitoring technology

(1) Apply digital system monitoring

Digital monitoring entails leveraging information technology to establish a digital management system, develop monitoring protocols, and convert bridge disease data into structural characteristic data to facilitate maintenance operations. This system enables the monitoring of stress positions on the bridge, assessment of stress characteristics at key locations, and evaluation of the bridge’s structural bearing capacity. Additionally, it tracks changes in stiffness, residual deformation, elasticity, and deflection under vehicle loading, automating data collection and processing for continuous real-time monitoring regardless of weather conditions.

For instance, in the case of a large bridge with a 20-year construction span and a 12.5 m width, supported by concrete slab beams and subjected to a designed load of hang-100 and car-20, the digital monitoring system revealed several issues. Water seepage was detected in the third span, and transverse cracks were observed in some span beams. To address these concerns, a monitoring device was deployed to track longitudinal deformation in the main span section. Monitoring points were established at the 3rd to 5th beam span sections, yielding the following results: First, the overall calibrated stiffness of the bridge, determined to be 3.91×10^6 kN·m^2, was notably lower than the theoretical stiffness of 7.75×10^6 kN·m^2, indicating a substantial reduction in structural stiffness. Specifically, the calibrated stiffness in the 3rd to 5th sections was 9.0×10^5 kN·m^2, 18.3% higher than the theoretical stiffness, suggesting significant lateral stiffness variation. Secondly, structural elasticity was assessed based on rebound position change curves, revealing an average daily rebound time of 0.8–0.85 s and a maximum deflection rebound time of 0.9–1.58 s, correlating with vehicle driving times. The prolonged rebound time of 2–3.7 s, attributed to heavy vehicle loads and slow driving speeds, underscored the impact of traffic patterns on structural behavior. Thirdly, finite element analysis determined the transverse distribution coefficient under loading conditions. Discrepancies between measured and theoretical values for beams 3, 5, and 6 indicated weak transverse connections and integrity issues, highlighting the need for corrective measures to address these concerns.

Following digital analysis, it was determined that the bridge exhibited safety hazards. To address this, the maintenance program must prioritize mitigating the decline in bridge stiffness. Reinforcement measures should be selected to enhance the bridge's bending capacity [4]. Additionally, attention should be given to reinforcing the girder plate articulation joints to optimize the structure's overall height and alleviate uneven force distribution. Implementation of preventive reinforcement devices is recommended to enhance plate and girder bending capacity, thereby prolonging the bridge's service life [5].

(2) Applying building information modeling (BIM) technology for monitoring

BIM technology should be utilized to establish a visualization platform. Sensors serve as data collection devices to detect information regarding bridge cracks, structural deformations, and other anomalies. A data acquisition system is utilized to transmit sensor data and bridge monitoring processes, ensuring synchronous collection and transmission of high-precision data and images [6]. Through the implementation of a bridge BIM platform, state information and dynamic data across various stages of the bridge's lifecycle are stored and managed. Additionally, the system's early warning module is utilized to promptly alert regarding the bridge's safety status and any potential issues.

BIM technology plays a central role in constructing three-dimensional bridge models to facilitate the visual representation of monitoring outcomes. The modeling procedure involves creating 1:1 models based on detailed construction drawings of the large-scale bridge, with assembly conducted meticulously according to abutment and pier elevations [7]. Following the modeling phase, environmental state data surrounding the bridge are organized to ascertain the presence of any significant issues. Control points are established to comprehensively analyze potential subsidence and deviation problems in key structures like abutments and piers, aiding in the precise selection and placement of monitoring points and sensors. Structural data collected by the sensors enable section-wise inspection of the bridge, with detection data uploaded to the platform for visual analysis. Leveraging the excellent visualization capabilities of BIM models, the distribution of bridge ailments can be directly showcased. The addition of a temporal element to the 3D model allows for the display of bridge ailments over time, establishing a 4D visualization platform to identify and exhibit bridge ailment information within the BIM model via 3D drawings. Within the BIM system, bridge state limits can be defined, triggering the early warning system if detection data surpasses these limits, and facilitating real-time monitoring of the bridge's safety status for managers [8].

(3) Applying real-time kinematic global positioning system (RTK-GPS) technology for monitoring

The analysis of displacement changes in major structures of large bridges under various conditions such as earthquakes, wind, temperature, and loads is essential for monitoring bridge damage. RTK-GPS technology, a type of real-time dynamic monitoring technology, is employed to obtain GPS coordinates of monitoring points. In large-scale bridge monitoring systems, the setup typically includes a control center, communication station, reference station, and monitoring station [9]. The monitoring station receives signals from the base station and satellites, obtains coordinates under GPS software, and transmits them to the monitoring center. Upon receiving data from different monitoring points, the processing software is utilized for analysis and data acquisition. For instance, in cable bridges, displacement data in horizontal, vertical, and other directions are obtained and stored in a database, facilitating managers in evaluating the bridge structure's health status. During data processing, the primary goal is to gather displacement and rotation angle information of the bridge in various directions and analyze load displacement, wind speed displacement, and temperature displacement data based on measured bridge load, wind direction, and temperature data. The data processing phase involves a transformation of bridge monitoring position coordinates, and consideration of temperature, wind, and traffic effects on key bridge components. With the implementation of GPS displacement monitoring systems, time-history curves of different monitoring points are successfully obtained, providing information on amplitude and vibration frequency. Spectrum analysis yields power spectrum curves of monitoring positions, enabling comparison with design theoretical values to diagnose the safety state of the bridge structure. In bridge monitoring data management, RTK GPS enables visual management. A dynamic monitoring database should be established to update and back up data timely, supporting data sharing and visual display through images. Managers can analyze dynamic changes in bridge structures and evaluate bridge health status through visual images [10].

4. Conclusion

The safety of large bridges is of utmost importance given the potential risks associated with various safety accidents. Therefore, prioritizing effective bridge management and maintenance is crucial to ensure their safe use. Detection technology and monitoring technology play vital roles during the construction, management, and maintenance phases of large bridges. With a plethora of technology options available, relevant personnel need to select appropriate detection and monitoring methods tailored to the specific characteristics of each technology. By aligning these methods with the management needs of large bridges, accurate bridge status data can be obtained. This data serves as a foundation for supporting bridge maintenance and management efforts, ultimately contributing to the creation of a safer transportation environment.

Disclosure statement

The authors declare no conflict of interest.

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