Research Progress and Future Prospects of Bridge Health Monitoring

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Abstract. At present, with the rapid development of new bridges, the prominent contradiction between the high demand for service safety and service quality of China's in-service bridges and the lack of actual performance of structures is becoming more and more reflected. In order to solve this problem, vigorously developing bridge health monitoring technology has become one of the important means. The purpose of this paper is to provide an overview of the parameter processing and evaluation and maintenance of bridge health monitoring, including the collection, transmission, processing, and evaluation of monitoring data, and distinguishes between two different evaluation methods based on time-varying reliability theory and those based on historical measurement data. The article also provides an overview of the current challenges in the field of bridge health monitoring and an outlook for future directions.

Keywords: bridge health monitoring, monitoring parameters, bridge health assessment and maintenance.

1. Introduction

In recent decades, with the rapid development of China's economy, China's modern bridges have made achievements in terms of construction scale and scientific and technological level, which have ranked among the top in the world. According to statistics, there are more than 800,000 highway bridges and more than 200,000 railway bridges in the country, and there are also a large number of urban overpasses and viaducts [1]. A bridge is a building that provides crossing capacity for railways, roads, channels, pipelines, pedestrians, etc., including rivers, valleys, or other transportation routes [2], as shown in Figure 1 and Figure 2.

Fig. 1 Bridge across the ocean

Fig. 2 Bridge across the valley

From ancient times to the present, bridges are closely related to our production and life, especially large and medium-span bridges are of great significance to local politics, economy, culture and national defense. Because of this, ensuring the safety of bridges plays a pivotal role in the national economy, and one of the important means to solve this problem is bridge health monitoring technology.

During the life cycle of bridges, various reasons such as material aging, environmental damage, and design theory will lead to the decline of the bearing capacity of bridge structures [3]. When it reaches a certain level, it will cause a series of major casualties. Between 2007 and 2012 alone, 37 bridges collapsed, nearly 60% of which were built after 1994, with bridges lasting less than 20 years. Based on this situation, bridge health monitoring technology will greatly reduce the risk of such accidents.

The so-called bridge health monitoring refers to the collection of bridge input and output information in an on-site, non-destructive, and real-time manner, and uses it to analyze the fluctuation, deterioration, and damage characteristics of bridge performance, so as to provide decision support for management and maintenance [4]. In recent years, major breakthroughs have been made in bridge health monitoring technologies such as sensor technology, GIS technology and non-destructive testing technology. Gao Bo et al. [5] studied on the basis of the modal confidence criterion, established a fitness function to meet the optimal layout of the sensor, and adopted the adaptive adjustment of the attenuation factor α in the gravitational constant G, which enhanced the optimization ability of the gravitational search algorithm, so as to optimize the placement of the sensor. Cheng Penggen et al. [6] realized the interaction between GIS and other modules with the help of GIS development kit GISDK of GIS software Maptitute, and the proposed system currently realizes many functions such as database entry of monitoring data, backup and recovery of database, and access to database through LAN. Svendsen et al. [7] proposed a hybrid SHM framework that combines numerical models and machine learning methods, and provides Level I, II, and III damage detection for structural diagnosis or decision assistance. At present, it can be seen that bridge health monitoring effectively combines modern sensing technology, network communication technology and signal analysis and processing technology. For example, GIS technology can integrate various bridge-related information into a system for management, thereby improving the functionality of the system and improving the interaction between the system and users [8].

In general, the research significance of bridge health monitoring mainly lies in the accumulation of bridge health monitoring system design and scientific research materials, and the ultimate goal is to realize the diagnosis and status assessment of bridge damage [9]. From the perspective of today's overall development situation, the development of bridge safety evaluation and prediction technology under complex conditions to improve the service safety performance of bridge structures has long become a major demand under the national sustainable development strategy in the new era, and it is also a research difficulty and hot spot in the academic community [10].

In this article, we will list the parameters commonly used in bridge monitoring and describe in detail the relationship between these parameters and the health status of the bridge. Sort out the process of collecting, processing, analyzing, and presenting such data; Identify the methods and indicators for health assessment, and review the corresponding maintenance and repair strategies; Finally, this paper summarizes and discusses the application prospects of bridge health monitoring in the future.

2. Bridge health monitoring parameters and their treatment

In actual engineering, because different bridge types have different structural characteristics and force characteristics, different monitoring methods will be adopted in the selection of monitoring parameters according to the different factors such as vulnerable components and safety incentives in the actual operation of the bridge [11]. The diagram below illustrates the selection of different monitoring parameters:

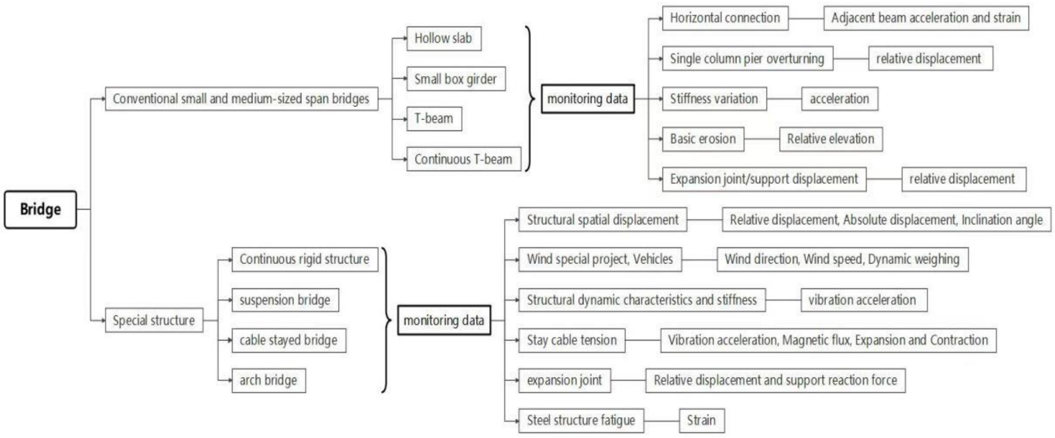

Fig. 3 Schematic diagram of monitoring parameter selection

Some of the commonly used monitoring parameters include factors such as structural displacement, vibration, and temperature. The structural displacement caused by external loads and environmental factors reflects the stiffness of the entire bridge structure and is one of the important parameters for bridge safety state assessment [12]. For example, Martinez et al. [13] used the deflection data provided by the displacement sensor to calculate the stiffness curve of the bridge length and used the combined iterative method to calculate the relative bridge stiffness profile, which has been proved to be suitable for damage localization and quantification. Vibration, as the most obvious response to the overall change of the bridge, is very reliable to evaluate the quality of the bridge and the quality of operation [14]. For example, Chang [15] and others used 19 accelerometers and 1 anemometer to conduct environmental vibration tests on a long-span suspension bridge in Hong Kong to determine the health status of the bridge. Similarly, the temperature action in the bridge will produce large deformation and stress on the bridge structure, and the effect of superimposition with other loads may cause the safety of the bridge to decrease. Especially for some special bridges, the impact of temperature can even exceed the dead load and live load, which directly damages the durability and operational safety of the bridge [16]. For example, OBrien et al. [17] collected temperature data from culvert bridges in Slovenia for 2 years and demonstrated that the damage indicator is sensitive to temperature changes, thus verifying that temperature can be used as a proxy for bridge damage. In summary, the use of the above parameters as the basis for bridge health monitoring is very representative and scientific and can directly and accurately reflect the real-time status of the bridge.

For the monitoring data mentioned above, the entire monitoring system needs to collect, transmit, process and display it throughout the process. The process is shown in the following figure:

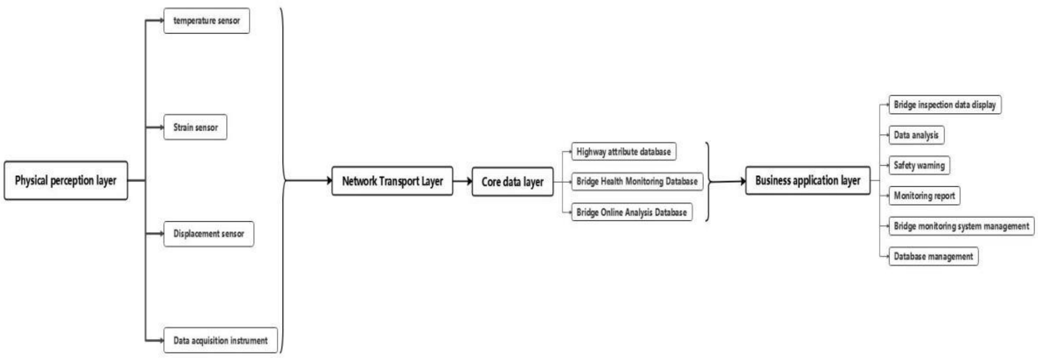

Fig. 4 Monitoring data processing flow charts

First of all, it is necessary to collect data with the help of sensor subsystems and select different sensors for different monitoring priorities. For example, the small vibrations generated by the vehicle and wind load can be monitored with the help of SD1221L accelerometers; For monitoring large vibrations such as earthquakes, ADXL202-type acceleration sensing is mainly used [18].

In order to ensure the integrity and reliability of the data, the entire transmission structure is divided into three layers, and the input and output of each layer are kept intact and need to be verified and confirmed. The three layers are the data acquisition layer, the data layer, and the application layer [19].

In terms of data processing, there are also differences in the processing methods for different types of monitoring data. Due to the noise of the collected measured vibration data, noise reduction is required [20]. Xiong Chunbao et al. [21] proposed an EEMD-wavelet threshold combined filtering method to improve the accuracy of noise in view of the influence of noise in the detection signal. The RDT-ITD method was used to identify the structural modal parameters. Finally, the above method is applied to the actual case and combined with the finite element results for comparative analysis. When dealing with the effects caused by temperature, wavelet decomposition and wavelet reconstruction are usually used to strip away the low-frequency temperature effects, and the effects after stripping are analyzed in depth, but the temperature effects of stripping are not treated as redundant data [22]. The entire data processing is corrected, summarized, compared and analyzed in the background information platform, so as to backcalculate and evaluate the real-time status of the bridge.

All monitoring results need to be presented through the monitoring platform, which is why they need to be visualized and the corresponding database built. Use BIM technology to complete data integration and dynamic response; SQL is used to establish a monitoring database, and finally realize the real-time monitoring and early warning function of security dynamics in the BIM monitoring platform [23].

However, with the advancement of bridge maintenance management processes and the widespread application of sensor technology, monitoring data is accumulating, and with it, a large amount of data based on different structures and complex sources· At present, the era of big data for bridge safety operation and maintenance has arrived, and how to effectively solve the problem of monitoring data in bridge SHM is a great challenge in the field of bridge health monitoring.

3. Bridge Health Assessment & Maintenance

Bridge health assessment is the most critical part of the entire bridge health management system, and its assessment results are directly related to subsequent reinforcement and maintenance measures. Its main task is to evaluate and predict the current and future environmental effects and load effects of the bridge's structural status [24]. For a complex structure like a bridge, the evaluation index covers a wide range and has many influencing factors. At present, the main focus is on temperature, fatigue damage, structural use status, and safety and reliability evaluation [25].

In general, the methods of bridge health assessment can be roughly divided into two categories: one is based on the time-varying reliability theory, which tries to explore the logical and factual relationship between the structural state of the bridge and a series of variables; The other type is the evaluation method based on historical measurement data, which affirms the uncertainty between the state of the bridge structure and the variables, and usually uses artificial intelligence methods such as Bayesian and artificial neural networks to achieve the purpose of evaluation and prediction.

The essence of the evaluation method based on the time-varying reliability theory is to analyze the structural state in the dimension of time according to the existing theoretical or experimental results, and when the unfavorable factors occur at the same time with an unacceptable probability, give them appropriate indicators and weights and carry out combined analysis. Common analysis methods include finite element modeling, statistical analysis, and accelerated testing. Kim et al. [26] proposed a fuzzy-based evaluation system for reinforced concrete building structures, in which the standard estimation results and their weights were expressed by Choquet fuzzy integrals. At the same time, a status index will be provided to determine recommendations for future maintenance and management. Stewart et al. [27] constructed a spatial transient reliability analysis model to predict the possibility and degree of cracking of reinforced concrete structures under chloride ion erosion. This model discretizes the reinforced concrete surface into a large number of elements and random fields and characterizes the variability of concrete damage in the region. A predictive corrosion initiation and propagation model is established to track the evolution of component corrosion processes, so as to determine the magnitude of the change in the degree of damage caused by the change of time. Croce et al. [28] used the cluster analysis method based on the Gaussian model to derive the stochastic models of reinforcement yield and concrete compressive models from the secondary database of test results, and objectively extracted the material classes and related probability density functions. Different reinforced concrete grades and degradation conditions are considered, so as to study the influence of steel corrosion on the time-reliability curve of reinforced concrete structures.

The essence of the evaluation method based on historical measurement data is to analyze the time series on the probability distribution of the structural state of the bridge according to the obtained measurement results. When the unfavorable factors are related to the probability distribution characteristics of a certain state of the structure, they are given corresponding weights. Wang Feiqiu et al. [29] established a bridge construction safety risk assessment index system based on the 4MIE analysis method, and also used BP neural network to establish a safety risk assessment model for bridge construction across existing high-speed railways and selected the field bridge as the research object for evaluation and empirical evidence, which reflects its scientificity and feasibility. Maroni et al. [30] applied Bayesian networks to the scour risk assessment of bridges for the first time, using it to describe the conditional dependence between the random variables involved, and using the scouring and river flow characteristic data to update the depth distribution of scouring, so as to achieve a more rigorous estimation of the scouring risk with only limited data, and significantly reduce the uncertainty of the undetected bridge scouring depth. It can be seen that the effective evaluation method can provide a good theoretical basis for the subsequent maintenance and reinforcement of the bridge and reduce the time and economic cost of reinforcement.

As China gradually enters the "after-construction market", the reinforcement and maintenance of bridges have also ushered in a corresponding golden age. At present, most of the bridges built in China in the early days are also unable to withstand the gradually increasing traffic and people due to the narrow net width of the bridge deck and the lack of live load safety reserves, followed by the reinforcement of old bridges. Obviously, the reinforcement and maintenance of bridges have become the key to strengthening the overall structural performance of bridges.

In view of the corrosion problem of steel bars, the pasted steel plate reinforcement method is the first choice. The pasting steel plate reinforcement method refers to the use of binders or anchor bolts to bond the weak part of the steel plate and the concrete tension zone to form a whole, so as to improve the bending bearing capacity of the bridge. Guo Shihui et al. [31] used the electrochemical corrosion of the five-piece test beam, the bending reinforcement method of pasting steel plate at the bottom of the beam for the three-piece beam, and the combined bending and shear reinforcement method for one beam, and the combination of finite element analysis and bending experiment, which showed that the two reinforcement methods can significantly improve the stiffness and bearing capacity of the RC beam.

In the face of the stress hysteresis effect of reinforcing materials, the external prestressed tendon reinforcement method can fundamentally solve such problems, give full play to the high tensile performance of reinforcing materials, and improve the utilization rate of materials. Miao Jianbao et al. [32] aimed at the problem that the external prestressed reinforcement structure may fail without warning due to insufficient ductility in the ultimate state and established an in vitro prestressed reinforcement method with displacement ductility coefficient as the index by using the conjugate beam method. Combined with the experimental analysis, the effects of different reinforcement methods, the existence of initial internal forces and the effective height on the ductility of the structure were studied.

In general, the reinforcement technology of China's bridges is currently becoming more and more perfect, and bridges of different types and different environments suffer from different types of diseases, traffic volume and construction conditions, etc., and the reinforcement and maintenance methods adopted are also different. Choosing the appropriate reinforcement and maintenance method will greatly improve the service life and use function of the bridge.

4. Future Trends & Summary

In the whole construction process of the bridge, it will be affected by many factors such as materials and design, which is why it is necessary to conduct in-depth research on the quality inspection of the bridge. In the whole management process, it is necessary to scientifically evaluate the quality defects through non-destructive detection methods, which reflects the extremely important application value of bridge health monitoring technology .[23] The monitoring platform can provide real-time and continuous internal force and deformation evolution generated by the bridge's own mechanism, identify the damage location and damage degree of the bridge structure, so as to realize the intelligent perception of the service performance, durability performance and reliable performance of the structure, and improve the safety and economy of the bridge [33].

At present, with the promotion and application of bridge health monitoring technology in major bridges, there are also some opportunities and challenges. There is room for improvement in the accuracy, difficulty of noise resistance, and service life of existing monitoring equipment [34]. At the same time, the current health monitoring system in China is basically strong monitoring and weak diagnosis, and the processing and diagnosis of monitoring data need to be improved [35]. In addition to some of the problems mentioned above, there are many other practical problems that are not mentioned in practical engineering applications. There is still a long way to go in order to establish a comprehensive bridge health monitoring system, which needs to be continuously improved and refined.

Due to the huge amount of data collected, there are also data challenges in bridge monitoring technology, and a good solution is to create a "digital twin" of the bridge. As a virtual representation of the physical world, digital twin technology has the advantage of being able to update data in near real time as it is collected, feed back to the physical entity, and execute "what-if" scenarios to assess bridge risk and predict the relevant performance of the bridge [36]. In addition, the popularization and development of deep learning technology will greatly promote the integration of bridge appearance inspection and SHM data, so that the two can be used in an integrated manner, and successfully change the current pattern of separating detection and monitoring status assessment [37]. At the same time, the evaluation method based on visual monitoring has been gradually applied and verified in various bridge inspection tasks such as crack identification and deformation monitoring due to its advantages of non-contact and high accuracy [38].

In summary, in the future, the research and development directions of bridge health monitoring systems mainly include: (1) the optimal arrangement of sensors, (2) the exploration of damage recognition of the system itself, (3) the effective and accurate bridge health assessment theory and the proposal of optimization algorithms based on data processing, and the development of appropriate intelligent control technologies [39].

In the future, bridge health detection technology is bound to carry out deeper research around these directions, so as to realize the comprehensive application of bridge health monitoring system and burst out new vitality in the field of bridge engineering. It is expected that China's bridge health monitoring technology will continue to develop and advance steadily in the future.

References

[1] Shao Xudong, Chen Zhengqing, Gu Anbang, et al. Bridge Engineering[M]. China Communications Press.2019.4. Beijing

[2] Shen Ruili, Liu Zhanhui, Tang Maolin, et al. Cable load-bearing bridge [M]. People's Communications Press. 2021.2. Beijing.

[3] ZHOU Yue, ZHU Yi, LI Gaotang, et al. Guangzhou Architecture,2019,47(04):3-7.

[4] Yi Tinghua, Zheng Xu, Yang Donghui, et al. Lightweight design method for structural health monitoring system of small and medium-span bridges[J]. Journal of Vibration Engineering,2023,36(2):458-466.

[5] WANG Lingbo, WANG Qiuling, ZHU Zhao, et al. China Journal of Highway and Transport,2021,34(12):25-45.

[6] Gen C P, Jun L D, Zhong S W, et al.Bridge Structural Health Monitoring and Management System Based on GPS and GIS Techniques[J].Journal of Highway & Transportation Research & Development, 2004.

[7] Katam,,Rakesh 等.A review on structural health monitoring: past to present[J]. INNOVATIVE INFRASTRUCTURE SOLUTIONS,2023,8(9):1-20.

[8] LIU Gang. Bridge structure health monitoring method of non-destructive testing technology[J]. Chinese Science and Technology Journal Database (Citation Edition) Engineering Technology,2024(4):0168-0171.

[9] Shan Deshan,Luo Lingfeng,Li Qiao. Research progress of bridge health monitoring in 2020[J]. Journal of Civil and Environmental Engineering,2021,43(S1):129-134.

[10] Gou Hongye, Liu Chang, Ban Xinlin, et al. Journal of Traffic and Transportation Engineering,2022,22(01):1-23.

[11] MU Yukun. Solving the Adaptation Problem of "Health Bracelet"——Design of Monitoring Parameters Based on the Safety and Long-term Performance of Bridge Structure[J]. China Highway,2022, (10):30-33.

[12] Liu Xiaping, Sun Zhuo, Yang Hong, Cai Kahong, Cheng Jingyang. Earthquake Engineering and Engineering Vibration,2013,33(3):176-18.

[13] Martinez, D., Malekjafarian, A., & OBrien, E. (2020). Bridge health monitoring using deflection measurements under random traffic. Structural Control and Health Monitoring, 27(9), e2593.

[14] Liu Hongtao, Geng Dong, Wang Le. Research on data processing method of bridge vibration monitoring[J]. Science and Technology Innovation and Application,2023,13(19):145-148.

[15] Chang, C. C., Chang, T. Y. P., & Zhang, Q. W. (2001). Ambient vibration of long-span cable-stayed bridge. Journal of bridge engineering, 6(1), 46-53.

[16] Xiao L, Cai J, Yang Y, et al. Research progress on the role and effect of bridge temperature in 2020[J]. Journal of Civil and Environmental Engineering,2021,43(S1):167-174.

[17] OBrien, E. J., Heitner, B., Žnidarič, A., Schoefs, F., Causse, G., & Yalamas, T. (2020). Validation of bridge health monitoring system using temperature as a proxy for damage. Structural Control and Health Monitoring, 27(9), e2588.

[18] Zhu Bin. Application of wireless sensor network in bridge health monitoring[J]. China Highway,2020, (11):152-153.DOI:10.13468/j.cnki.chw.2020.11.056.

[19] Huang Yujun, Li Shiyun, Zhang Jinquan. Application of information technology in bridge health monitoring system[J]. Guangdong Communication Technology,2023,43(03):60-63.

[20] Ntotsios E, Papadimitriou C, Panetsos P, et al. Bridge health monitoring system based on vibration measurements[J]. Bulletin of Earthquake Engineering, 2009, 7: 469-483.

[21] Xiong Chunbao, Yu Lina, Chang Xiangyu. Modal parameter identification of bridge structure based on EEMD-wavelet threshold denoising[J]. Journal of Tianjin University (Natural Science and Engineering Technology),2020,53(04):378-385.

[22] Li Ning, Zhu Chenhui. Research on the longitudinal displacement delay effect of support based on bridge health monitoring[J]. Shandong Transportation Science and Technology,2020(5):52-5573.

[23] Wang Yuanfu. Research on the status quo of bridge intelligent health monitoring technology and application[J]. Transportation World,2023, (25):147-149.

[24] Zhang Fang, Zhang Kaiquan, Deng Jiechao, et al. Research progress of bridge evaluation and reinforcement in 2020[J]. Journal of Civil and Environmental Engineering,2021,43(S1):152-166.)

[25] Editorial Department of China Journal of Highway and Transport. China Journal of Highway and Transport,2021,34(02):1-97.

[26] Kim Y M, Kim C K, Hong S G. Fuzzy based state assessment for reinforced concrete building structures[J]. Engineering Structures, 2006, 28(9): 1286-1297.

[27] Stewart M G, Mullard J A. Spatial time-dependent reliability analysis of corrosion damage and the timing of first repair for RC structures[J]. Engineering structures, 2007, 29(7): 1457-1464.

[28] Croce P, Formichi P, Landi F. Influence of Reinforcing Steel Corrosion on Life Cycle Reliability Assessment of Existing RC Buildings. Buildings 2020, 10, 99[J].

[29] Wang Feiqiu, Huang Jianling, Fu Jing, et al. Safety risk assessment of construction of cross-existing high-speed railway bridge based on BP neural network[J]. Journal of Railway Science and Engineering,2019,16(05): 1129-1136.DOI: 10.19713/j.cnki.43-1423/u.2019.05.003.

[30] Maroni A, Tubaldi E, Val D V, et al. Using Bayesian networks for the assessment of underwater scour for road and railway bridges[J]. Structural Health Monitoring, 2021, 20(5): 2446-2460.

[31] Guo Shihui, Tang Huang, Zhang Jianren, et al. Experimental study on flexural performance of corroded reinforced concrete beams reinforced with steel plates[J]. Bridge Construction,2019,49(04):46-51.

[32] Miao Jianbao, Feng Wei, Xu Bing. Ductility analysis and experimental study of in vitro prestressed reinforced concrete beam[J]. World Bridges,2019,47(03):76-80.

[33] ZHAO Qingjie. Research on the status quo of bridge intelligent health monitoring technology and application[J]. Transportation World,2023, (10):7-10.

[34] WANG Yafei, YANG Junyu, ZHONG Jiwei, et al. Highway Engineering,2024,49(01):45-52.

[35] Li Zihua. Shanxi Architecture,2014,40(04):152-153.D

[36] Ye C, Butler L, Bartek C, et al. A digital twin of bridges for structural health monitoring[C]//12th International Workshop on Structural Health Monitoring 2019. Stanford University, 2019.

[37] Sun Limin, Shang Zhiqiang, Xia Ye. China Journal of Highway and Transport,2019,32(11):1-20.

[38] Wangyuanfu. Research on the status quo of intelligent health monitoring technology and application of bridges[J]. Transportation World,2023, (25):147-149.

[39] Wu Qimin. Jiangxi Building Materials,2016, (10):153-154.