Bridge health monitoring and evaluation system

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ABSTRACT: To understand the health status of the bridge, this paper explores how to use the bridge health monitoring and evaluation system for bridge health monitoring, management, and evaluation. It also expounds in detail the role of other subsystems. In this system, a sensor system can monitor the bridge in real time to obtain the basic data of the normal operation of a bridge. At the same time, the daily manual inspection work is carried out. We will receive data through the data collection, transmission, and processing subsystem for the next operation. Finally, the evaluation subsystem can use the data to carry out a series of calculations and analyses, and then the bridge health status score can be obtained.

1. Introduction

In the 21st century, with the continuous development of the economy, people's demand for bridge transportation conditions is also increasing. By the end of 2019, there were 878,300 highways and bridges nationwide, covering 60,634,600 meters, an increase of 26,800 and 4,948,600 meters from the previous year. Among them, there were 5,716 extra-large bridges with a total length of 10,332,300 meters, and 108,344 bridges with a total length of 29,237,500 meters[1]. People's attention to the problem of bridge safety and applicability is constantly increasing. Because the bridge has a long life cycle, large scale and the operation of the check is difficult, and it is easily affected by the weather and climate conditions, bridge’s structure will inevitably produce a variety of injuries[2, 3, 4, 5, 6]. But the resources consumed by relying only on human resources to do a good job of bridge health testing are too large and restrictive.

With the continuous development of science and technology, the health monitoring technology of Bridges has also occupied an important position[7] [8]. This technology facilitates the relevant technical maintenance personnel to understand the health state of Bridges at all times and do a good job in the maintenance of Bridges. Based on the bridge health monitoring system, some daily inspection is carried out to judge the health state of the bridge, which provides a scientific basis for the maintenance and management.

Therefore, the emergence of bridge health monitoring and evaluation system is very important, which is of great significance in the application of the bridge. It can not only effectively feedback the use of the bridge in real time, but also send out early warning signals in time when abnormal conditions occur on the bridge and present specific information to the relevant technicians in order to respond in the shortest time. It provides decision-making plans to avoid a wide range of quality or safety issues and saves a lot of human and material resources.

2. The concept of bridge health monitoring and evaluation system

The bridge health monitoring and evaluation system refers to the real-time monitoring and
management measures that use a series of science and technology to ensure that the bridge can maintain its safety and applicability. It is the use of various types of sensors in the daily operation of the bridge. An advanced system that monitors its structural status, evaluates and judges the bridge structure and deck paving information in normal use, and evaluates its health status [9].

From the perspective of engineering project management, the assessment of the health status of a bridge structure mainly determines whether it meets applicability, durability, safety, reliability, economy and coordination. The health status of the bridge is mainly evaluated from two aspects. On the one hand, whether the bridge deck has changed, causing cracks and other diseases, which affects the applicability of the bridge; on the other hand, we should consider whether the structure of the bridge has changed and whether the structural bearing capacity has decreased, which affects the safety of the bridge. Due to the limitations of the sensor work, some of the bridge deck paving diseases mentioned in the former cannot be sensed by the sensor. Therefore, while the sensor system is working, manual daily inspection assistance should also be used to enrich the reliability of the data for the more objective and effective results.

3. Research on bridge health monitoring system at home and abroad

The exploration of bridge structural health monitoring has more than eighty years. The concept of bridge structural health monitoring was first proposed in the United States in the 1950s, the reason was the destruction of the Tacoma suspension bridge accident in 1940, the cause of the damage was the wind load. This accident led American experts begin to notice the importance of determining the safety of bridge structures by monitoring the state of the bridge's environment[10] [12]. However, due to the limitation of scientific development at that time, as well as the incomplete understanding of health monitoring information, experts and scholars did not achieve substantial results. In the late 1980s, with the development of artificial intelligence technology, computer technology, sensing technology, and data signal processing technology, some European and American countries put forward the concept of bridge health monitoring again and successfully applied it to the bridge. The research focus was mostly on the process of data collection. For example, sensors such as strain, displacement, and temperature were installed on the Sunshine Skyway Bridge in the United States to collect data[13]. The structural health monitoring system of the Foyle Steel Box Girder Bridge was installed in Ireland to monitor the temperature, deflection, strain, and various other environmental factors of the bridge[10]. The Siggent Hall Bridge in Switzerland has installed a health monitoring system during construction. It was equipped with 2 inclinators, 58 fiber-optic deformation sensors to monitor its displacement, deformation, and bending during construction and subsequent use[14]. As the concept of bridge health monitoring system is constantly updated, it has attracted the attention of many Asian countries, and more and more countries begin to apply this system to their Bridges for real-time monitoring.

Although the concept of bridge structural health monitoring was introduced lately in China, its progress is also very rapid. For example, Qingma Bridge, Humen Bridge, and Jiangyin Yangtze River Bridge have all applied this system in the early days. In the early stage of technology, there are still some problems such as low sensitivity and large construction cost[15] [16]. From the germination of technology to the outbreak period to the trough period, it is not until the progress of sensor technology, computer analysis technology, artificial intelligence technology, information acquisition and processing that Chinese research on structural health monitoring system has entered a period of rapid development. More theoretical studies of experts have successively proposed, such as the research on the local variables and the overall monitoring variables based on the structural health monitoring system of the Dongying Yellow River Highway Bridge, and the safety early warning integrated system for the structural health monitoring system of the Xiamen BRT bridge. In addition, various bridge health monitoring indicators and specifications have been continuously proposed, making the application of this system more standardized.
4. Composition of bridge health monitoring and evaluation system

4.1. Sensor System

Because of the complexity of the bridge and the factors that affect the health of the bridge structure are diversified, leading to different locations and types of bridge diseases. Therefore, there are more requirements for the selection of sensor types, and full consideration should be given to the various factors. The type of sensor is required to ensure the possibility to collect disease information. From the specific application of the sensor, there are some sensor types following for monitoring:

1. Humidity thermometer: used to monitor atmospheric temperature and relative humidity; temperature and humidity measurement values in various periods (hour, day, year); relationship between main beam deflection and temperature and humidity changes.

2. Temperature sensor: the temperature time history of steel components, concrete, and air; temperature measurement and temperature difference in various periods (hour, day, year); the relationship between displacement value and temperature change.

3. Displacement meter: the measured value of the displacement of the support and the main girder in each time period (hour, day, year); the lateral displacement and rotation angle change of the bridge; the relationship between the displacement of the expansion joint and the support and environmental factors.

4. Inclinometer: the relative displacement between the measuring points in each time period (hour, day, year); the relationship between the displacement of the stiffening beam, the main tower and the environmental factors.

5. Vibrating cable gauge: acceleration response time history of each measuring point; acceleration amplitude of each frequency; power spectrum; amplitude and phase difference of accelerometers of each measuring point; vertical speed, torsion speed, displacement and rotation angle Time history; peak displacement and rotation angle of characteristic points, mean and standard deviation of displacement and rotation angle in different time periods; structural dynamic characteristics, such as natural frequency, modal (and participation factor), damping ratio, modal energy conversion rate; specific Simple harmonic vibration and its corresponding natural frequency under external excitation conditions.

6. Strain sensor: the amplitude and fluctuation of strain, stress and internal force; verification of the design value of strain, stress, force and bending moment at the local interface of the component; continuous time-history strain value of each measuring point; structural internal force, stress, strain changes with external temperature, traffic load, and other loads; predict extreme values based on statistical distribution; fatigue factor analysis based on rain flow counting.

4.2. The system of data acquisition and transmission

The system of data acquisition and transmission is mainly used for the information which is collected and transmitted by the sensor. The sensor collected all sorts of temperature, humidity, natural frequency, the structure of the displacement, stress, and strain information, and they are converted into a digital signal, through a serial port server, switch, and industrial control equipment, such as real-time data transmission, and uploaded to the monitoring platform of information management for the bridge health assessment. The design of the system focuses on the following aspects:

1. The data acquisition system can continue to work around the clock, and is not affected by severe weather.

2. The transmission network structure must be safe and reliable, and its design must meet the corresponding technical standards.

3. Electrical, installation specifications, machinery, and communication protocols should use relevant national specifications or compatible standards.

4. The data acquisition and transmission system should have real-time self-diagnosis function, and be able to judge data abnormalities, sensor failures, functional abnormalities or subsystem failures.

5. The remote control of data can be realized, and the sampling parameters can be changed.
remotely. 
(6) The system should have real-time data collection, storage and management functions.

4.3. The system of data processing
The data or discrete data collected through real-time monitoring of a single sensor can hardly reflect the true situation of the overall performance state of the bridge structure, so data processing is required to provide a basis for subsequent health assessment[18].

Data processing is divided into two parts, one is data preprocessing, and the other is data secondary processing. The former plays a role in real-time evaluation, processing the data collected by sensors through real-time monitoring, and uses mathematical statistics to calculate method to obtain the average value, highest value, lowest value, standard deviation and other data in the corresponding time. These data are used for the primary early warning comparison object and the data for reference in the final evaluation; the latter is the comparison between the monitoring data of each category further analysis[19].

4.4. Primary warning system for structural safety
The primary early warning system of the bridge structure is an indispensable subsystem in the system. The subsystem uses the model comparison method to determine whether to issue an alarm by comparing the real-time monitoring data of the sensor with the preset threshold. Relevant personnel are warned to check the bridge data to make a preliminary prediction of the health of the bridge[20]. Among them, the real-time monitoring data of the sensor used for comparison is the average value in each time period, and the predetermined threshold is the data of the unit component of the bridge within the acceptable range, and the data changes with the increase of the life of the bridge. The workflow of this subsystem is shown in the figure below.

![Figure 1. Flow chart of the primary early warning system.](image)

4.5. Bridge health status assessment system

4.5.1. Evaluation method of bridge health state
For the assessment and maintenance of bridges, the safety assessment method of bridges is one of the important links[21]. The safety evaluation method is to evaluate the overall safety performance of the bridge by calculating the obtained data. It can not only determine whether the bridge is reliable, but
also provide a scientific maintenance plan for bridge maintenance. The methods of safety assessment are also diverse, each one has its own advantages and disadvantages and scope of application[6]. The following are common evaluation methods.

1. Routine comprehensive evaluation. This method uses weighted arithmetic average, weighted geometric average, and a hybrid evaluation method of comprehensive algorithm and geometric average, but it is not suitable for problems that are difficult to describe quantitatively.

2. Fuzzy comprehensive evaluation method. This method is based on fuzzy mathematics and quantifies factors with unclear boundaries. This method introduces the concept of membership function and solves the contradiction between the ambiguity of things and the certainty of the algorithm. But the evaluators are subjective, and it is difficult to select fuzzy algorithm and determine the degree of membership.

3. Appearance investigation and evaluation method. This is an assessment standard based on the "Highway Bridge and Culvert Maintenance Code", which requires comprehensive technical detection of the bridge, but its value depends largely on the detection experience of the evaluators themselves, and the evaluation value has great randomness.

4. Finite element simulation of carrying capacity. It is to simplify several beams into a beam, to find out the bearing capacity of it, according to the transverse distribution coefficient of load to find out the bearing capacity of the whole bridge.

5. Expert system evaluation method. This is the combination of expert knowledge and experience with the computer system for evaluation, which can use the knowledge and experience of experts to solve the uncertain factors in bridge design, construction and management, but at the same time, it is difficult to directly evaluate the complex bridge structure and numerous factors only by relying on the experience of experts.

6. Fuzzy neural network method. It is a method that organically combines the mechanism of neural network with the reasoning mechanism of fuzzy logic, which can take the respective advantages of the two technologies, learn from each other and reduce the influence of human factors on the evaluation process[22].

7. Grey relational degree evaluation method. This is based on the grey system theory, taking the time series as the object, and finally making the sorting method for each sequence.

8. Analytic Hierarchy Process. By determining the relationship between the importance degree and the mutual influence of each bridge component, the multi-level evaluation and scoring can simplify a lot of complicated evaluation work, which is scientific, simple, and practical.

4.5.2. Assessment of bridge health status

The assessment of the bridge health status is based on a comprehensive calculation score based on its applicability, structural safety and other aspects, and finally the health status of the bridge and its score value are obtained. The scoring uses the analytic hierarchy process. The analytic hierarchy process is to hierarchize and adjust the various factors that affect the normal working state of the bridge, and summarize the factors that have similar effects on the state of the bridge units to form a layer, thereby establishing a multi-level comprehensive evaluation and evaluation system[18] [23].

The daily inspection data of the bridge and the structural health monitoring data were weighted and synthesized, and the overall health status assessment information of the bridge was obtained by integrating the indicators of each layer[24]. The specific calculation method is as follows:

For the evaluation index of bridge health state, Hearn[25] has the following definition form:

\[ PI = \sum_{i} K_i F_i(a,b,c,...) \]

Among the number, \( PI \) is the status indicator; \( K_i \) is the weight of disease; \( F_i \) is the disease; a, b, c ... are the attribute of disease.

The bridge health status assessment in the American Bridge Archives Database System (NBIS) is obtained from the health assessment conclusions of the main components of each bridge, and all the
main components are based on the comparison between the current health status of the bridge structure and the completed structure to obtain the overall health status of the bridge, the scoring range is 0-9 points.

The overall health status score R of the bridge is obtained based on the following formula.

\[
R = \frac{\sum_{i=1}^{n} RW_i}{\sum_{i=1}^{n} W_i} = \sum_{i=1}^{n} R_i K_i
\]  

(2)

Among the number, \( i=1..., n \) is the element of the bridge that has an important influence on the overall health state of the bridge; \( W_i \) is the weight of main components on the whole bridge; \( K_i \) is the standard value of \( W_i \); \( R_i \) is a score of the worst condition on each bridge unit, which includes the analysis results of the bridge.

\[
R_i = R_i W_{i1} + R_i W_{i2}
\]  

(3)

Among the number, \( W_{i1} \) is the weight of daily manual detection data; \( W_{i2} \) is the data directly monitored by the system, and there is \( W_{i1} + W_{i2} = 1 \).

Through the data processing, the bridge health status evaluation table in the following table can be obtained.

**Table 1. Bridge health evaluation table.**

| Score | Description of state | Description of structural health monitoring results | Description of applicability | Measures of safeguard |
|-------|-----------------------|----------------------------------------------------|------------------------------|-----------------------|
| 9     | Excellent             | The overall state of the bridge is better than the "initial state" | Better than current norms | No need to repair     |
| 8     | Very good             | The overall state of the bridge is equivalent to the "initial state" | Corresponding to current standards | Without repair; List the items that need special attention during the next inspection cycle |
| 7     | Good, but it has a few small questions | The overall state of the bridge is the same as the "initial state", and no defects are found | That's better than the current minimum standards | No immediate repair plan; Check for the possibility of further testing |
| 6     | Fine, there is a slight degradation of the structural unit | The overall state of the bridge is the same as the "initial state". Although minor "damage" occurs in the secondary components, the overall performance is not affected | Corresponding to the current minimum standards | Repaired at the end of next quarter; Add it to the work program |
| 5     | Acceptable - All major components are in good condition, but there may be small section losses, cracks, or scour | The overall state of the bridge is slightly lower than the "initial state", and no damage is found in the main components, while large damage appears in the secondary components, but it has little influence on the overall performance | A little better than the acceptable minimum affluence | Put in the current plan; Repair in the current quarter, and choose the first fix |
| 4     | Poor - section has a loss, degradation, peeling, or corrosion | The overall state of the bridge is lower than the "initial state", and the main components are damaged, which has a great impact on the overall performance | Meet the minimum affluence | Priority. Repair in this quarter, review the relative priority of the work plan and adjust the worksheet if possible |
Severe - Section has had a loss, degradation, or scouring has seriously affected the main structural elements. Local damage may occur. Fatigue cracks may occur in steel structures or shear cracks may occur in concrete structures.

| Hazard                  | Condition                                                                 | Score | Repair Priority          |
|-------------------------|---------------------------------------------------------------------------|-------|--------------------------|
| 3                       | The overall state of the bridge is lower than the "initial state" to a large extent, and the main components are seriously damaged, which has a great impact on the overall performance. | Unacceptable and it needs major repair | High priority; Repair in this season and schedule repairs as early as possible |
| 2                       | There are serious defects in the overall state of the bridge, and the damage of the main components is very serious, which seriously affects the overall performance. | Unacceptable, it needs more replacement | Highest priority; Interrupt other work if necessary; take basic or emergency supplementary measures (notice, ban truck, limit speed, etc.) |
| 1                       | The overall performance of the bridge is lost, and the carrying capacity of the main components has been seriously lost. | The score value cannot be used | Shut down the service and wait for repair |
| 0                       | The overall performance of the bridge is completely lost.                   | Close the bridge | Close the bridge and cannot be maintained. |

5. The future research direction
At present, the bridge health monitoring and evaluation system still have many deficiencies, and some functions cannot meet the requirements of bridge construction. It needs to be further improved[26]; in order to improve the system, further research can be carried out in the following areas in the future.

(1) Optimize the layout of sensors. Because of the diversification of bridge disease information, the types and number of sensors required are also huge, but the number of sensors is also limited. How to reduce the number of sensors while achieving the purpose of complete information monitoring requires us to further think, namely How to optimize the placement of sensors, the placement of measuring points is the key.

(2) Collection of effective data. The data monitored through the sensors is undoubtedly a huge amount of various kinds. How to accurately identify the disease information we need from this information and use effective data to evaluate the integrity of the bridge? This is what we need to conduct further research.

6. Conclusion
The technology involved in the bridge health monitoring and evaluation system is complex and diverse. The basic data of the bridge can be obtained by real-time monitoring of the bridge through the sensor subsystem. Then, the system can realize the purpose of assessing the health status of the bridge after data transmission and processing. The development and progress of this system is of great significance to the operation and management of bridges, which means that the application of intelligent information technology has replaced traditional manual detection methods, saving manpower and material resources, and enabling resources to be reasonably configured and utilized. There are more possibilities for management, structural condition assessment and timely maintenance of bridges.

The future development and progress will depend on the joint efforts of us. We should improve the bridge health monitoring and evaluation system through continuous research.
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