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ORIGINAL PAPER

# Research on bridge structure SAM based on real-time monitoring

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## Abstract

To study the problems of frequent omissions and false alarms in the early warning system due to defects in the safety assessment method (SAM) of the existing bridge health monitoring systems (BHMS). In this paper, the current safety evaluation methods of BHMS are deeply studied through fuzzy comprehensive evaluation method and derive a new type of bridge health monitoring system SAM based on the safety evaluation vector. At the same time, combined with the concept of membership function, the result vector is accurately quantified, and a specific evaluation method for evaluating the safety level of the bridge structure is obtained. Combining the data of the three bridge health detection systems of 3 × 30 m continuous girder bridge, simply supported beam bridge, and steel–concrete composite girder bridge in the Beijing Metro Line 5 project, the daily and monthly safety assessment results of the three BHMS were verified. The research results show that the structural SAM proposed in this paper can accurately and in real-time evaluate the safety status of small and medium-span simply supported bridge structures. However, for the evaluation of continuous girder bridges and composite girder bridges, it is necessary to make specific judgments based on the actual conditions of the bridges. Moreover, the research in this paper can also consolidate the theoretical foundation for establishing the bridge structure monitoring data, early warning model. The research method in this paper can promote the further development of the bridge structural health monitoring system.

**Keywords** BHMS · SAM · Bridge risk level · Real-time monitoring

## 1 Introduction

With the rapid development of China's bridge construction technology, the future development direction of bridge engineering that the development direction based on fast construction is gradually being replaced by the direction based on maintenance. A bridge health monitoring and early warning system based on data analysis and prediction can be established through sensor technology, data acquisition technology, and data correction technology. In data analysis and prediction model establishment, setting a structural SAM that can encompass all factors that affect the safety of the bridge structure is one of the critical factors that affect the accuracy of data prediction [1–3].

Existing bridge structures are more complicated in force form, which leads to more factors affecting structural safety assessment than traditional structures. A research hotspot in the current academic circle is how to systematically quantify all influencing factors through structural SAM and effectively evaluate the safety level of bridge structures. In the current bridge standards, three main types of data collection technology solutions can be used for bridge safety assessment: regular inspections, load testing, and long-term health monitoring. In a complex natural environment, due to the influence of many random loads and the aging and fatigue effects of the structure itself, it is not easy to quantify the safety assessment status of bridge structures, especially for complex bridges structures, accurately. Under normal circumstances, bridge health inspections are mainly supplemented by regular and load tests, and long-term health inspections are the main. Therefore, it is essential to analyze the bridge structure that can cover all the factors that affect the bridge structure's safety and conduct in-depth research on the structural SAM based on real-time monitoring data [4–6].

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For the research of BHMS, domestic and foreign scholars have proposed several structural SAMs. By introducing the concepts of support vector machine and Particle Swarm Optimization Algorithm, Wu [7] determined the parameters of the bridge structure health status detection model. Agdas et al. [8] combined Fuzzy Analytic Hierarchy Process with fuzzy logic and established a set of models that can effectively assess bridge risks. Through in-depth analysis of prior perception, Cappello et al. [9, 10] studied the influence of human factors on determining the parameters for the bridge health monitoring algorithm, especially involving various empirical parameters that need to be established by expert seminars. Zhao [11] used RFID systems and personal digital assistants to develop a new urban railway structure inspection system. Agdas et al. [8] conducted research on in-service bridges' health inspection and evaluation methods, especially visual inspection and structural health monitoring, as a comparative study of bridge health assessment methods. Farhey [12] studied the performance of the instrument system for bridge health monitoring. His team found that in the long-term bridge health monitoring system, the performance of the instrument system will directly affect the accuracy of the detection data. Based on these findings, the team proposed that the bridge health assessment method be adjusted over time.

Similar model studies include a bridge risk assessment model based on fuzzy group decision-making and a structural SAM based on the analytic hierarchy process and the data envelopment concepts.

Because the safety assessment of BHMS generally requires high accuracy, especially in evaluating the safety level for bridge structures with many influencing factors. The monitoring data analysis method based on regular inspections and load tests has gradually shifted to a bridge early warning model centred on real-time monitoring. Yuan [13] and Zhao [14] studied the application of the level 2 safety assessment framework for concrete-filled steel tube arch bridges based on Chinese bridge standards. They obtained real-time dynamic monitoring data of the structure through finite element model update technology. Zhang [15] has researched joint optimization bridge risk assessment model based on the concept of extended confidence rule base and verified the application of extended confidence rule base in BHMS. Rahmatalla et al. [16] demonstrated the predictability of the finite element model by combining the finite element modal analysis with the operating vibration waveform generated by the vehicle and proposed the concept of hierarchical early warning.

However, the existing SAM still has the following problems: first of all, the early SAM cannot effectively envelop all the safety influencing factors of bridge structures, which results in low prediction accuracy. Such as the analytic hierarchy process and bridge risk assessment model based on data envelopment analysis. Second, the existing structural SAM pays too much attention to the maximum value in the result vector when processing it and ignores the rest of the data. Such as the traditional SAM based on the principle of maximum membership degree or the principle of posting schedule. Finally, the risk assessment model established based on historical data greatly reduces data processing efficiency in the monitoring system as the number of data increases, resulting in frequent omissions and false alarms in the early warning system [17, 18].

Because of the above problems, this paper proposes a method that can effectively solve the problems of frequent omissions and false alarms in the early warning system due to the defects of the existing SAM of BHMS. At the same time, this paper combines FCEM with monitoring data to establish FCEM for bridge monitoring items. And realize the real-time assessment of bridge structural safety based on the continuously updated data of the monitoring system. Finally, combined with the health monitoring system data of three small and medium-sized bridges of 3 × 30 m continuous girder bridge, simply supported girder bridge and steel–concrete composite girder bridge of Beijing Metro Line 5, the health monitoring system of the three bridges was verified.

## 2 Research on common result vector analysis methods and membership functions

In the research of bridge structure SAM, the first problem to be solved is the accurate quantification of the result vector and the sufficient envelope of the data. Then the following two issues will be focused on: (1) how to accurately quantify the result vector so that bridge managers can conduct a practical and real-time safety level assessment; (2) how to establish a set of practical membership functions to envelop the influencing factors of all bridge safety states. Another meaning of the membership functions is to quantify all the factors that affect the safety of the bridge structure to facilitate the next step, that is, to complete the processing of the result vector.

### 2.1 Research on the result vector analysis method

#### 2.1.1 The necessity of introducing weight analysis method

It is common to use the principle of maximum membership for analysis for the relationship between the bridge safety level and the result vector. However, because the results obtained by the maximum membership evaluation method only consider the maximum value without other values, the analysis of the result vector is not comprehensive enough.

Based on this situation, some researchers used the closeness principle to analyze the result vector. As an improved method of the direction for maximum membership, the direction of closeness considers the relationship between the five values of the result vector. It gives a more reasonable analysis method than the principle of maximum membership. However, when analyzing the result vector in this paper, it is found that for some exceptional cases, whether the code of maximum membership degree or the direction of closeness, it is not accurate enough to evaluate the final result.

Examples are as follows:

1. Suppose there is a result vector, as Eq. (1):

$$B_1 = (0.501, 0, 0, 0, 0.499) \tag{1}$$

Evaluation level, as Eq. (2):

$$V = (V_1, V_2, V_3, V_4, V_5) = (\mathrm{L}evel1, Level2, Level3, Level4, Level5) \tag{2}$$

According to the principle of maximum membership degree, the security level corresponding to the result vector $B_1$ is level 1.

2. According to the principle of closeness, calculate five proximity according to the following Eq. (3).

$$N(B, D_i) = 1 - \frac{1}{30}\sum_{k=1}^{5} \left|\mu_B(V_k) - \mu_D(V_k)\right| k \tag{3}$$

where $B$ is the result vector; $D_i$ is the fuzzy feature subset; $\mu_B(V_k)$ is the calculation formula of the result vector corresponding to each feature fuzzy subset.

For the result vector $B_1$, by Eq. (3), the five closeness values are calculated as:

$$N(B_1, D_1) = 0.9002, \quad N(B_1, D_2) = 0.8501,$$
$$N(B_1, D_3) = 0.8167;$$
$$N(B_1, D_4) = 0.8333,$$
$$N(B_1, D_5) = 0.8998.$$

According to the principle of closeness, the security level is also determined to be level 1. However, intuitively, the vector value corresponding to the level 1 security level is only 0.04 larger than the vector value corresponding to the level 5 security level. It is unacceptable that the security level of the recognition result vector $\mathrm{B}_1$ is level 1. On the other hand, suppose there is a result vector:

$$B_1 = (0.499, 0, 0, 0, 0.501)$$

According to the principle of maximum membership degree, the security level is five. According to Eq. (3), the five closeness values are calculated as:

$$N(B_2, D_1) = 0.8998, \quad N(B_2, D_2) = 0.8499,$$
$$N(B_2, D_3) = 0.8166, \quad N(B_2, D_4) = 0.8334,$$
$$N(B_2, D_5) = 0.9002.$$

According to the principle of closeness, the security level is also determined to be level 5.

3. By comparing the evaluation results of $B_1$ and $B_2$, conclusions can be drawn. When a particular data item monitored by the bridge changes, it is easy to change the result vector from $B_1$ to $B_2$. At this time, the safety level of the bridge will suddenly change from one to five. In other words, the bridge in a safe state suddenly becomes a dangerous state that the bridge cannot be used anymore. This situation is unacceptable for assessing bridge safety levels, and a sound bridge safety level evaluation system should not have this situation.

Based on the above examples, it can be found that whether it is the principle of maximum membership degree or the improved approach degree principle analysis method, there are disadvantages of putting too much emphasis on the maximum value. When the maximum value in the result vector is close to other matters, the calculation results of these two methods are not suitable.

#### 2.1.2 Proposal of weight analysis method

It is unrealistic to define their security level as one to five for the several result vectors listed above. The evaluation results should move closer to the middle level. At the same time, only using the result vector to express the security level from one to five is not accurate enough. Based on the above problems, by giving the representative value of the bridge evaluation index scores, the five safety evaluation levels correspond to the five score segments, and the evaluation index scores are shown in Table 1. The specific security level content will be introduced later.

On this basis, this paper proposes a weight evaluation method. The central idea of the weight analysis method is to substitute each value in the structure vector into the same weight function *f*(*x*), and the obtained calculation result is regarded as the weight representing the five corresponding security levels. After that, multiply the weight and the median of the safety score interval defined and sum it up to get the final evaluation result. The security level represented

**Table 1** Bridge evaluation index score interval table

| Classification | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|
| Score interval | [90, 100] | [70, 90) | [50, 70) | [30, 50) | [0, 30) |
| Median score | 95 | 80 | 60 | 40 | 15 |

by this resulting vector can be obtained by substituting the obtained score value into the corresponding score interval.

The resulting vector is obtained, as Eq. (4):

$$B = (x_1, x_2, x_3, x_4, x_5) \tag{4}$$

According to Table 1, the safety level *V* represented by it can be quantified, as Eq. (5):

$$(V_1, V_2, V_3, V_4, V_5) = (95, 80, 60, 40, 15) \tag{5}$$

Then the calculation formula of the weight analysis method, as Eq. (6):

$$n = \frac{\sum_{i=1}^{5} f(x_i) \times V_i}{\sum_{i=1}^{5} f(x_i)}, \tag{6}$$

where $f(x_i)$ is the weight obtained by bringing the corresponding value in the result vector *B* into the function; $V_i$ is the score corresponding to different security levels; *n* is the score result obtained from the evaluation.

### 2.1.3 Research on the characteristics of the weight analysis method

It can be seen from the above formula that the selection of the weight function $f(x)$ will directly affect the result of the evaluation. Because, for any $i \in [1, 5]$, there is $x_i \in [0, 1][0, 1]$, and $\sum_{i=1}^{5} x_i = 1$. Therefore, the first derivative of $f(x)$ must meet the following conditions, as Eq. (7):

$$\frac{\mathrm{d}f(x)}{\mathrm{d}x} > 0. \tag{7}$$

The selected weight function $f(x)$ must be increasing to violate the fundamental principle that the larger the value in the result vector *B*, the more influential the safety is. Assuming that there is a single element $x_{\max}$ with the largest value in the result vector *B*, the weight ratio $m_i$ calculated by the weight function $f(x)$ between $x_{\max}$ and any other element $x_i$, as Eq. (8):

$$m_i = \frac{f(x_{\max})}{f(x_i)}. \tag{8}$$

When $f(x)$ takes the most commonly used one-variable linear function, the value of $m_i$ is the ratio of $x_{\max}$ to $x_i$, denoted as $m_j$, as Eq. (9):

$$m_j = \frac{x_{\max}}{x_i} \tag{9}$$

When the second derivative of $f(x)$ is greater than zero, as Eq. (10):

$$\frac{\mathrm{d}f^2(x)}{\mathrm{d}x^2} > 0 \tag{10}$$

From Eq. (10), it can be known that the value of $m_i$ will be greater than $m_j$. When the second derivative of the weight function $f(x)$ is greater than zero, the weight of the largest element $x_{\max}$ in the result vector B will increase. When the second derivative approaches positive infinity, as Eq. (11):

$$\frac{f(x_{\max})}{\sum_{i=1}^{5} f(x_i)} = 1. \tag{11}$$

The result obtained using the weight analysis method is only related to the element with the largest value in the result vector *B*. The results obtained using the weight analysis method are the same as those obtained using the principle of maximum membership.

### 2.1.4 Determination of weight function and weight vector

According to the above analysis results, the first derivative of the selected weight function $f(x)$ must be greater than zero. The second derivative should be appropriately greater than zero to reflect the importance of the maximum value in the result vector *B*.

Considering the convenience of calculation, this article chooses $f(x) = x^2$ as the weight analysis method's weight function. Therefore, the final formula for weight analysis, as Eq. (12):

$$n = \frac{\sum_{i=1}^{5} x_i^2 \times V_i}{\sum_{i=1}^{5} x_i^2}. \tag{12}$$

Using the weight analysis method to analyze the two result vectors mentioned above $B_1$ and $B_2$, the evaluation scores obtained are 55.16 and 54.84, respectively. Corresponding to the evaluation score interval, the safety level is all three. Moreover, when the maximum value of the result vector changes in a small range, it does not affect the final evaluation result. Using the weight analysis method can solve the problem that the calculation results of the principle of maximum membership and the direction of closeness are too heavy for the maximum value in the result vector.

According to the characteristics of the original data source when calculating the weight, the analysis methods for determining the weight can be divided into three categories: the subjective weighting method, the objective weighting method, and the combined weighting method. The subjective weighting method is an analytical method that determines the weight according to the emotional importance of each attribute by decision-makers (usually industry experts). The original data mainly come from the personal judgment of experts based on experience.

Commonly used subjective weighting methods include expert survey (Delphi method), analytic hierarchy process (AHP), binomial coefficient method, etc. Combined with the characteristics of the bridge structure of the research object, this paper will choose the Delphi method to determine the weight of the result vector. The Delphi method is based on the opinions and opinions of relevant experts or authoritative persons, and the survey object is limited to the expert level. This method was first used for technology development prediction and has been widely used in political, economic, cultural, and social development and other fields.

The working procedures of the Delphi method mainly include: organizing an expert group, drawing up an investigation outline, selecting the investigation objects, soliciting opinions in turn, and sorting out the investigation results. The main features of the expert investigation method are correspondence, multiple directions, anonymity, repetition, and concentration. It can also be seen that the Delphi method is more scientific and has a wide range of application prospects.

## 2.2 Research on commonly used membership functions

An appropriate range is required for each monitoring item to define which security level the data belongs to. The determination of the specified content of the membership function is the core of distinguishing different bridges and different monitoring systems. The criterion for determining the scope of the membership function: calculate the threshold of each measurement item specified in the specification. The security level is five when the monitoring data is near the regulatory point. According to the distance of the data away from the specification limit, the safety level will increase in turn.

### 2.2.1 Membership function model

Considering that the research object of this paper is bridge structure, the safety degree of bridge structure needs to be described by a certain amount of monitoring data. The corresponding membership function is established for each evaluation factor, classified into specific evaluation levels according to specific values. According to the bridge evaluation classification characteristics, the trapezoidal distribution is selected as the basic model of the membership function and adjusted as the membership model of each project. The specific membership function model is shown in Eq. (13):

$$u(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \le x < b \\ 1 & b \le x < c \\ \frac{d-x}{d-c} & c \le x < d \\ 0 & d \le x \end{cases}. \tag{13}$$

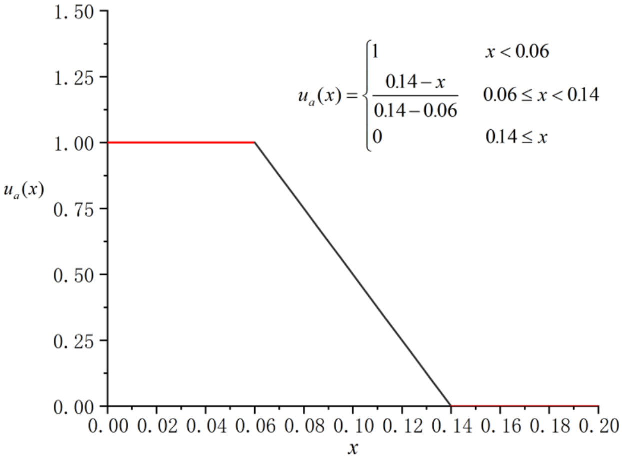


**Fig. 1** Membership function of one-level components

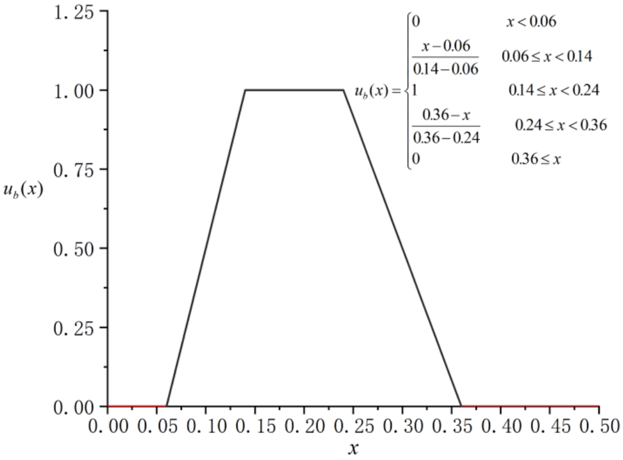


**Fig. 2** Membership function of two-level components

### 2.2.2 Establishment of membership function

A specific membership function can be obtained through Eq. (13) and combined with the threshold value of each factor in the above specification. Take structural deformation as an example here. Take the ratio of the measured data and the specification limit as the independent variable $x$. The five-level membership function of structural deformation is shown in Figs. 1, 2, 3, 4 and 5.

The membership functions for structural bridge cracks, beam stress, and joint expansion width can be derived using the same method.

## 2.3 Classification of security levels

According to the assessment method of the existing specifications on the technical condition of the bridge, it is not

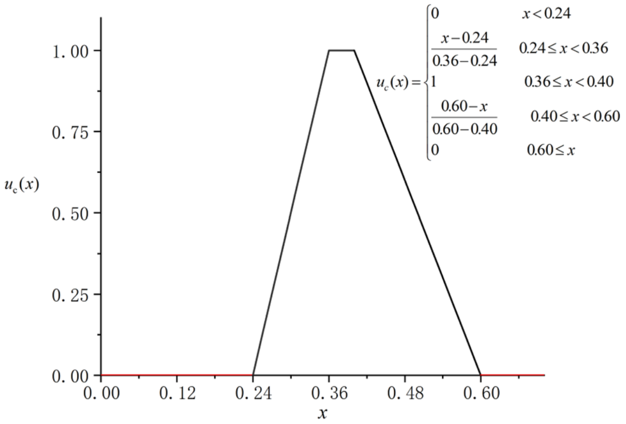


**Fig. 3** Membership function of three-level component

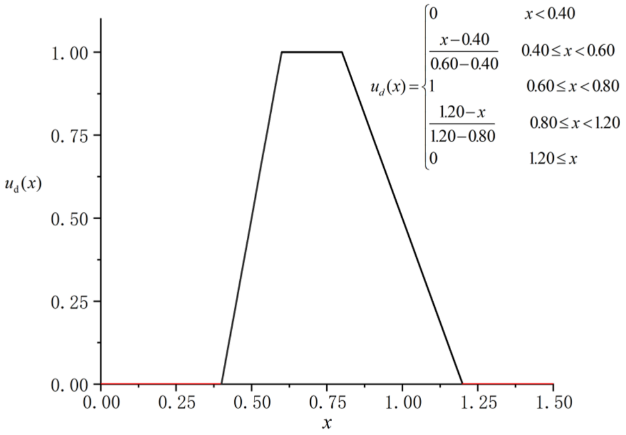


**Fig. 4** Membership function of four-level components

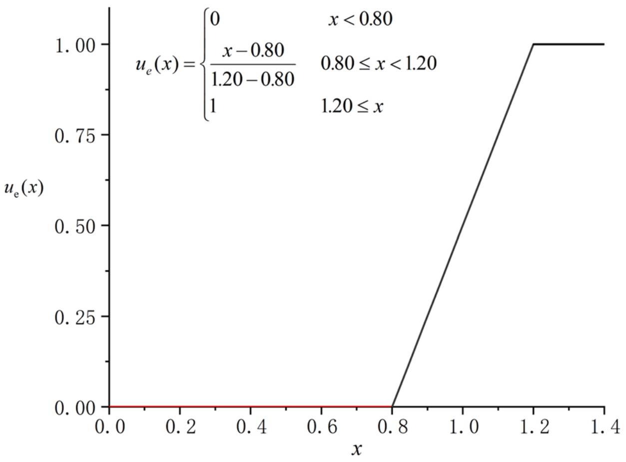


**Fig. 5** Membership function of five-level components

difficult to obtain the five types of safety assessment grades for the bridge. Discrete the structural safety assessment results according to 5 states and express them from one to five levels [19, 20]. The meanings of all levels are as follows:

Level 1: The bridge does not have structural safety issues. The components are usually working, and the values of each monitoring item are in a safe and sound range, and there is no need to do any treatment on the bridge;

Level 2: The bridge structure is safer. The components are usually working, and most of the monitoring items are less than the limit value and need to be repaired slightly without reinforcement;

Level 3: The safety of the bridge structure is average and at a passing grade. Each component can still work typically, some monitoring items are close to the limit value, or some members have minor diseases and need to be repaired without reinforcement;

Level 4: The safety of the bridge structure is poor. Some components cannot work typically, the values of most of the monitoring items are close to the limit, and the data of some monitoring items exceed the limit. After special inspection, they will be overhauled or reinforced;

Level 5: The bridge structure is dangerous with poor safety. Each component has serious diseases to varying degrees and shows a trend of continued expansion. The value of each monitoring item is greater than the standard value, and the bridge cannot be used anymore. It is necessary to check and determine how to deal with it.

## 3 Establishment of structural SAM

The structural SAM used in this paper combines FCAM with monitoring data to establish FCAM for bridge monitoring items. Through this method, the purpose of real-time assessment of bridge structure can be achieved by relying on the monitoring system's data. The establishment of the fuzzy comprehensive evaluation method generally requires four steps: determining the evaluation level of the structure, determining the comprehensive evaluation factor model, determining the evaluation weight vector, and establishing the membership function of each factor. The related issues of weight vector and membership function have been introduced above. The framework of the bridge structure safety assessment method is shown in Fig. 6.

The fuzzy comprehensive evaluation method is generally divided into the first-level fuzzy comprehensive evaluation and the second-level fuzzy comprehensive evaluation. In this paper, considering that many factors affect bridge structures' safety state, the second-level FCEM with higher accuracy is selected.

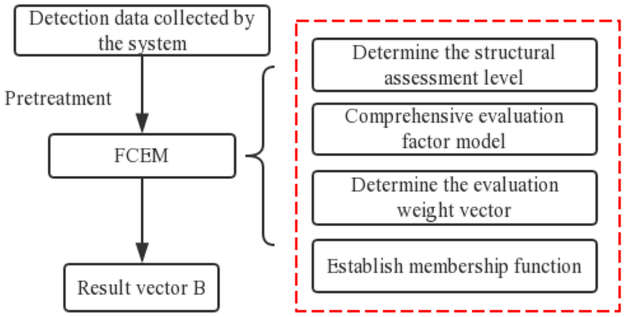


**Fig. 6** The framework of the safety assessment method of the bridge structure

### 3.1 Introduction of the second-level FCEM

Suppose the level 1 factor set is recorded as the structural layer, and the level 2 factor set corresponding to each structure of the structural layer is recorded as the factor layer.

1. Choose suitable models for FCEM.

   Commonly used models include $M(\bullet,+)$ model, $M(\text{exponentiation}, \wedge)$ model, $M(\wedge,\vee)$ model, etc. This article chooses the weighted average model that considers all factors, namely the $M(\bullet,+)$ model. This model comprehensively considers various factors and can retain the information of each factor, which is more suitable for the safety assessment of bridge structures.
2. Determine the membership function for each factor in the factor layer.

   The FCEM is a bottom-up evaluation method. The evaluation of each bottom factor must be achieved through its corresponding membership function. Suppose the monitoring data of the j-th factor of the i-th structure layer at a certain moment is. In that case, the evaluation vector calculated by the corresponding membership function is $B_{ij} = [b_{ij1}, b_{ij2}, b_{ij3}, b_{ij4}, b_{ij5}]^{\mathrm{T}}$.
3. Establish the secondary evaluation matrix $R_i$ of the structure layer

   For each structure $U_i$ in the structure layer, after each factor $U_{ij}$ below it is calculated by the corresponding membership function, the evaluation vector $B_{ij}$ obtained is assembled into a matrix, which is the secondary evaluation matrix $R_i$ of the structure $U_i$. The specific calculation method is shown in Eq. (14).

$$R_i = \left[B_{i1}\, B_{i2}\, \cdots\, B_{ij}\right] = \begin{bmatrix} b_{i11} & b_{i21} & \cdots & b_{ij1} \\ b_{i12} & b_{i22} & \cdots & b_{ij2} \\ \vdots & \vdots & \vdots & \vdots \\ b_{i15} & b_{i25} & \cdots & b_{ij5} \end{bmatrix} \tag{14}$$

4. FCEM of secondary indicators

   Assume that the weights assigned to the indicators $U_{i1}, U_{i2}, \ldots, U_{ij}$ of $U_i$ are $W_i = [a_{i1}, a_{i2} \cdots a_{ij}]^{\mathrm{T}}$ respectively. Use the weighted average model to calculate the secondary evaluation result vector for $W_i$ and $R_i$, namely, as Eq. (15):

$$B_i = R_i \cdot W_i = [b_{i1}, b_{i2}, \ldots b_{i5}]^{\mathrm{T}}, \tag{15}$$

   where $b_{iy} = \sum_{x=1}^{j} a_{ix} \cdot b_{ixy}\ y = 1, 2, \ldots 5$.
5. FCEM of the level 1 indicators.

   For each structure $[U_1, U_2, U_3, \ldots, U_m]$ in the structure layer, the level 2 evaluation result matrix $R = [B_1, B_2, B_3, \ldots, B_m]$ is obtained according to the FCEM of the level 2 indicators in the previous step. This matrix is multiplied by the weight W of the level 1 evaluation $B = R \cdot W$. The final evaluation vector B of the FCE of the level 1 index can be obtained. The specific calculation method is as Eq. (16).

$$B = R \cdot W = [B_1\, B_2\, \cdots\, B_m] \cdot \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix} = \begin{bmatrix} b_{11} & b_{21} & \cdots & b_{m1} \\ b_{12} & b_{22} & \cdots & b_{m2} \\ \vdots & \vdots & \vdots & \vdots \\ b_{15} & b_{25} & \cdots & b_{m5} \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{bmatrix}. \tag{16}$$

   Analyze the obtained result vector $B$ and get the final evaluation result. Then, the bridge structure's safety level can be determined.

### 3.2 Structural safety assessment method design process

The structural safety assessment design flow chart of the BHMS is shown in Fig. 7.

## 4 Establishment of BHMS

### 4.1 Monitoring system sensor arrangement

The bridge structure studied in this paper is a 3 × 30 m prestressed concrete continuous box girder bridge in the section of No. 14–17 piers in the interval between "North Exit of Huixin West Street and East of Datun Road" of Beijing Metro Line 5. The central monitoring contents include crack monitoring, support monitoring, beam stress monitoring, beam displacement monitoring, pier top displacement monitoring, and ambient temperature. The layout of monitoring points for the 3 × 30 m prestressed concrete continuous girder bridge at piers 14–17 is shown in Fig. 8, and the monitoring items are shown in Table 2.

The layout of the box girder sensor is shown in Fig. 9a, b is the sensor position check, Fig. 9c is the Keyence IL-S100 laser displacement sensor, and Fig. 9d is the strain gauge.

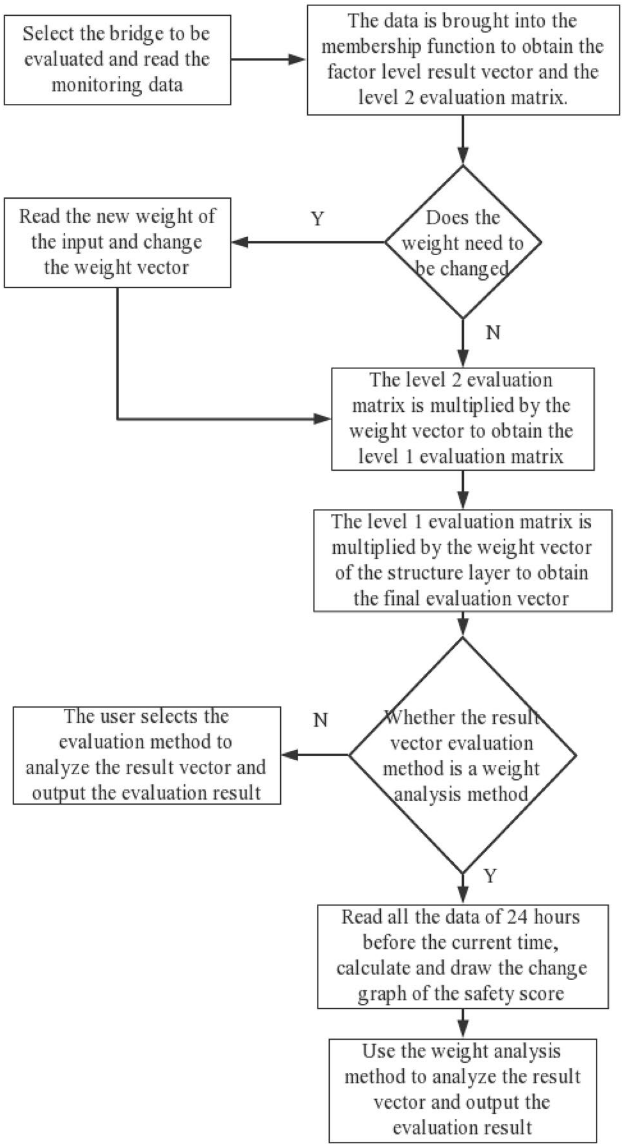


**Fig. 7** Flow chart of structural safety assessment design

Among them, the mid-span tensile stress monitoring point and the web stress monitoring point are strain gauges; The beam displacement monitoring point, the beam displacement in the transverse direction and along the bridge direction are all laser displacement sensors; The support deformation monitoring points include support longitudinal deformation displacement, support shear deformation displacement and vertical displacement. The sensors used in the detection system are all laser displacement sensors.

## 4.2 Data collection of BHMS

To ensure the safety of subway operations, the subway operation management department has carried out several special inspections and routine annual inspections. The test results show some diseases and problems in the bridge structure. As the operating life increases, the condition will change further. The existence of these defects has brought certain hidden dangers to the regular operation of the subway. To eliminate risks and improve safety protection, BHMS was installed on the elevated section of Beijing Metro Line 5 after certification by experts. The BHMS is mainly composed of information acquisition and safety evaluation. Information acquisition primarily refers to various sensors installed across multiple structure parts. After a series of remote transmissions, the collected structural response information is stored in a database for bridge maintenance managers to conduct a real-time safety assessment of the bridge structure. The flow chart of the monitoring system is shown in Fig. 10. Safety assessment analyzes and calculates the pre-processed information through structural mechanics theory to find structural damage and determine the impact of wear on the structure.

As part of the bridge health monitoring system, a total of 25 sets of sensors were installed on the $3 \times 30$ m prestressed concrete continuous girder bridge at piers 14–17. The detailed parameter information of the sensor is shown in Table 1. In the past, to verify the efficiency and accuracy of the sensor, the operating department would check the sensor data every specific period. Figure 11 is the data check on the horizontal and vertical displacement of the support at 7:17–7:24 on the morning of July 14, 2016. It can be seen from the check diagram that the dynamic displacement of the support is zero when there is no subway train passing, and the displacement will change when the train passes. Still, the displacement deformation is within the allowable range of the subway design specification. The specification stipulates that the longitudinal displacement of the plate rubber bearing shall not exceed 5 mm, and the lateral displacement shall not exceed 2 mm.

## 4.3 Determination of the weight vector

In the calculation of the FCEM, the weight vector of each structural layer and the weight vector of the factor layer need to be determined explicitly by the analytic hierarchy process. The specific steps of using the analytical hierarchy process are shown in Fig. 12.

Regarding the determination of the weight vector of each structural layer and factor layer, due to the insufficient content of the normative record, there are not many studies on FCE of the same type of BHMS at home and abroad. Therefore, this article chooses the expert survey method to judge different structural and factor layers' weight vectors. After consulting several experts, these experts have a good understanding of the bridge operation status of Metro Line 5, and the researchers made statistics and sorted out the expert survey opinions they gave. Try to balance the views of all

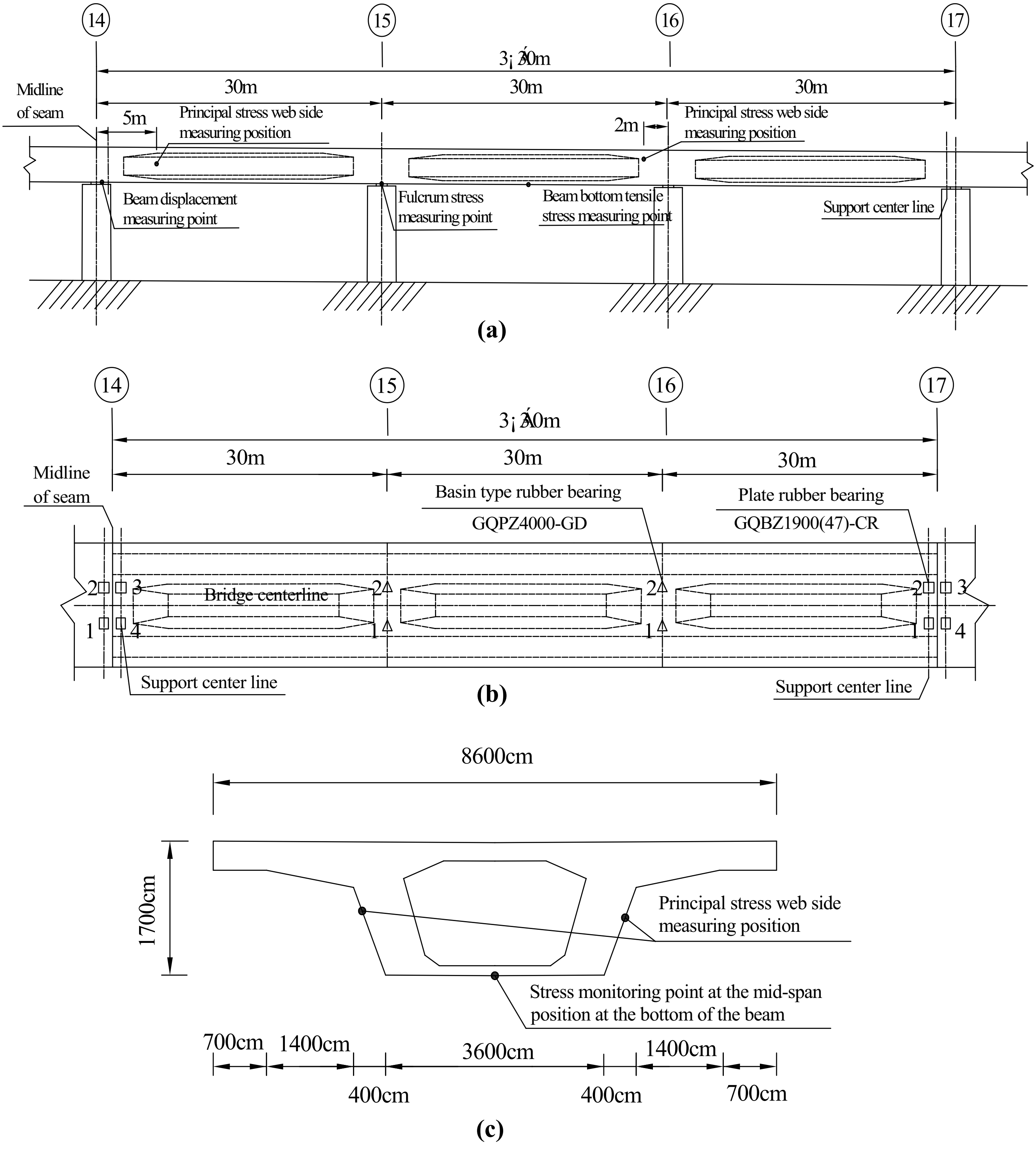


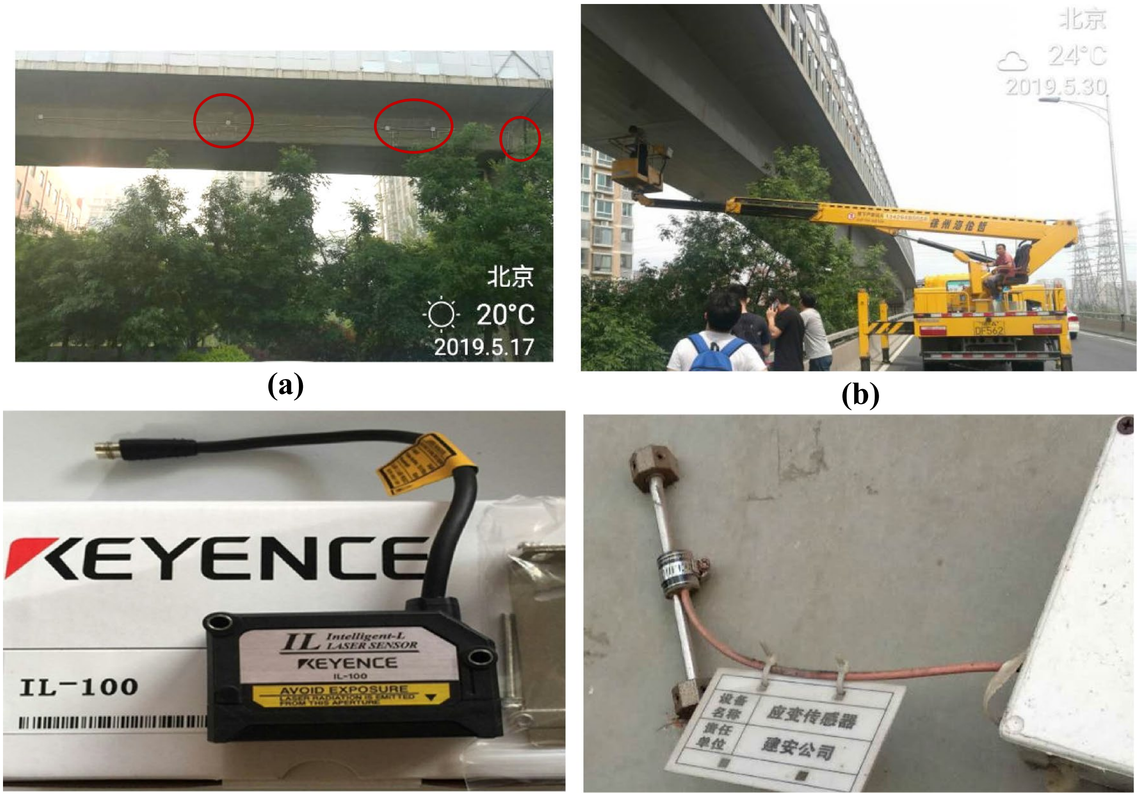
**Fig. 8** Layout of measuring points for 3 × 30 m prestressed concrete continuous beam bridge at piers 14–17: **a** schematic diagram of bridge elevation; **b** schematic diagram of the bridge; **c** cross-section of the beam

experts while looking for standard views on the weight vector. Take the factors contained in the beam factor layer in the comprehensive evaluation factor model as an example. Table 3 shows the weight vector judgment matrix after comprehensive statistics.

Checking the consistency of the judgment matrix shows that the average random consistency index R.I. of the 7-order matrix is 1.36. The calculation of the consistency proportional coefficient C.R. is as Eq. (17) and Eq. (18):

**Table 2** Monitoring items between piers 14–17

| Serial number | Equipment name | Monitoring accuracy | Monitoring items/uses | Number of monitoring locations |
|---|---|---|---|---|
| 1 | Ambient temperature sensor | 0.1 °C | Ambient temperature | 1 |
| 2 | Strain gauge | 1 με | Bottom stress of beam | 3 |
| 3 | Inclinometer | 0.03° | Lateral displacement of pier column | 1 |
| 4 | Inclinometer | 0.03° | Longitudinal displacement of pier column | 1 |
| 5 | Laser displacement sensor | 0.1 mm | Beam body transverse displacement | 1 |
| 6 | Laser displacement sensor | 0.1 mm | Beam body displacement along the bridge | 1 |
| 7 | Laser displacement sensor | 0.1 mm | Lateral displacement of the support | 1 |
| 8 | Laser displacement sensor | 0.1 mm | Vertical displacement of support | 1 |
| 9 | Laser displacement sensor | 0.1 mm | Bearing displacement along the bridge | 1 |
| 10 | Laser displacement sensor | 0.1 mm | Shear deformation of bearing | 1 |
| 11 | Strain gauge | 1 με | Principal stress of web side | 7 |
| 12 | Crack gauge | 0.1 mm | Beam crack monitoring | 6 |



(a) (b)

(c) (d)

**Fig. 9** The layout of the sensor: **a** arrangement of box girder sensors; **b** check the position of the sensor; **c** KEYENCE IL-S100 laser displacement sensor; **d** strain gauge

**Fig. 10** Design structure of bridge health monitoring system

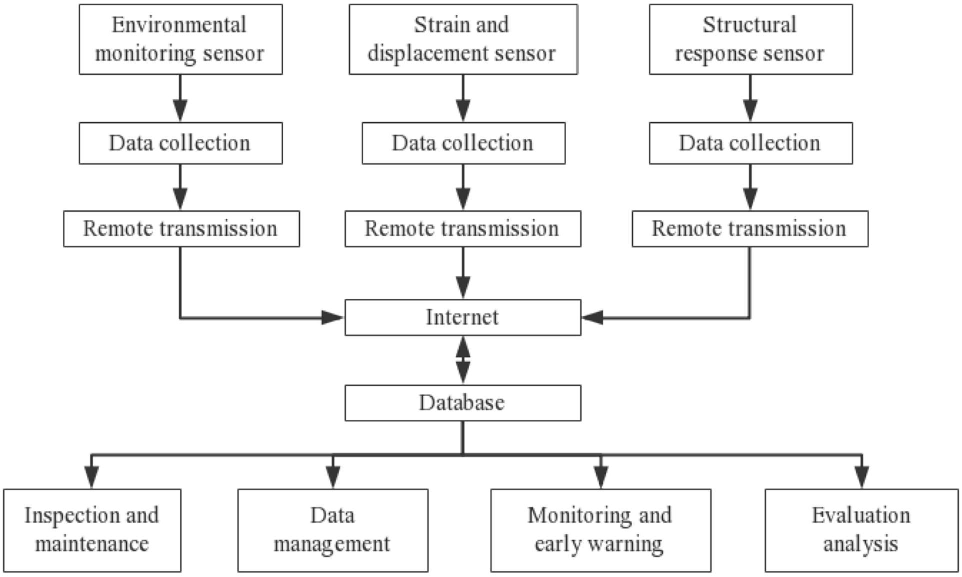
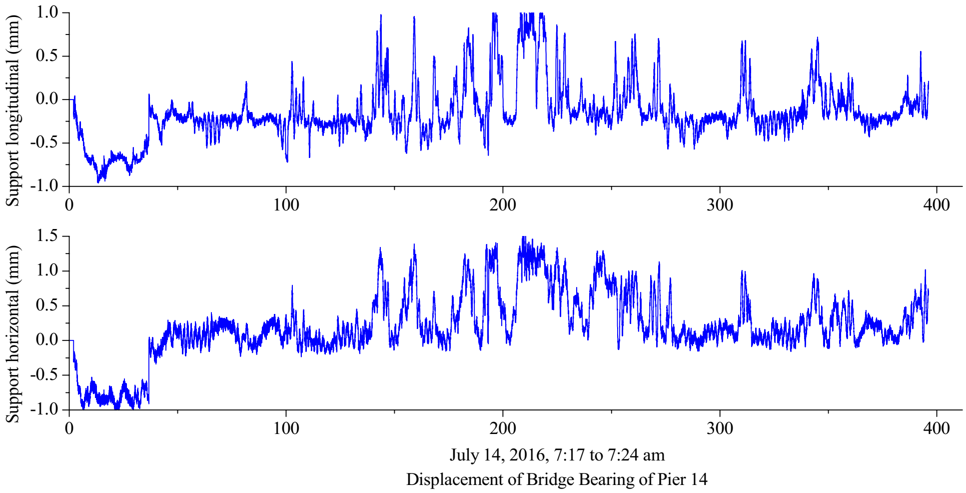


**Fig. 11** Data verification of No. 14 pier support. C.I. is the calculation consistency index; R.I. is the random consistency index; C.R. is the calculation consistency ratio coefficient



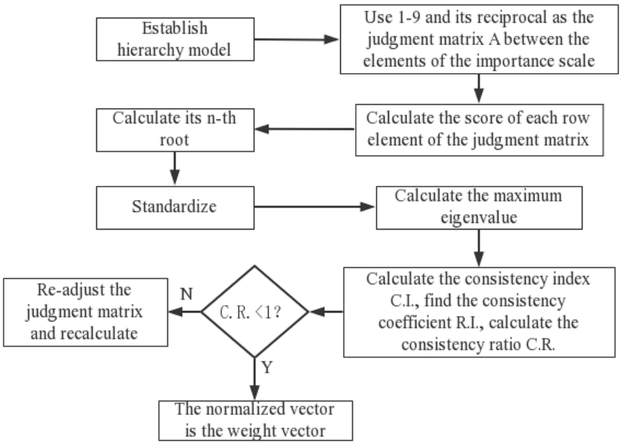


**Fig. 12** Flow chart for calculating weights by analytic hierarchy process. *C.I.* calculation consistency index, *R.I.* random consistency index, *C.R.* calculation consistency ratio coefficient

$$\text{C.I.} = \frac{\lambda_{\max} - n}{n - 1} = \frac{7.6735 - 7}{7 - 1} = 0.112 \tag{17}$$

$$\text{C.R.} = \frac{\text{C.I.}}{\text{R.I.}} = \frac{0.112}{1.36} = 0.0825 < 0.1, \tag{18}$$

where $\lambda_{\max}$ is the largest eigenvalue; $n$ is the order of the matrix.

It can be seen from Eq. (18) that the consistency of the matrix is acceptable, so the weight vector of each component of the beam is as shown in Eq. (19):

$$W = (0.212, 0.383, 0.094, 0.094, 0.142, 0.035, 0.034)^{\mathrm{T}}. \tag{19}$$

**Table 3** The weight judgment matrix of each factor of the beam body

| | The tensile stress of beam web | Beam crack | Lateral displacement of the beam | Longitudinal displacement of the beam | Beam mid-span stress | Expansion joint width | The relative displacement of steel–concrete interface |
|---|---|---|---|---|---|---|---|
| Tensile stress of beam web | 1 | 1/3 | 3 | 3 | 2 | 5 | 5 |
| Beam crack | 3 | 1 | 4 | 4 | 5 | 6 | 7 |
| Lateral displacement of beam | 1/3 | 1/4 | 1 | 1 | 1/3 | 5 | 4 |
| Longitudinal displacement of beam | 1/3 | 1/4 | 1 | 1 | 1/3 | 5 | 4 |
| Beam mid-span stress | 1/2 | 1/5 | 3 | 3 | 1 | 5 | 2 |
| Expansion joint width | 1/5 | 1/6 | 1/5 | 1/5 | 1/5 | 1 | 2 |
| Relative displacement of steel–concrete interface | 1/5 | 1/7 | 1/4 | 1/4 | 1/2 | 1/2 | 1 |

## 5 Verification and expansion of bridge health monitoring system

### 5.1 Processing of health monitoring system data

The data of each measurement item collected from the continuous girder bridge of piers 14–17 at 7 am on July 14, 2016, is selected as the sample data. Bring the sample data into the membership function of each factor, and verify the structural safety assessment method. The establishment of the comprehensive evaluation factor set is shown in Fig. 13.

#### 5.1.1 Single-factor analysis of beam body

According to the data recorded by the BHMS, the lateral displacement of the beam is 0.77 mm, and its displacement limit is 7.5 mm. The ratio of the measured value and the limit value is brought into the membership function of the displacement, and the evaluation vector of the lateral displacement of the beam is obtained as $(0.467,0.533,0,0,0)^T$ [21].

The longitudinal displacement of the beam is 4.66 mm, and the displacement limit is 7.5 mm. The ratio of the

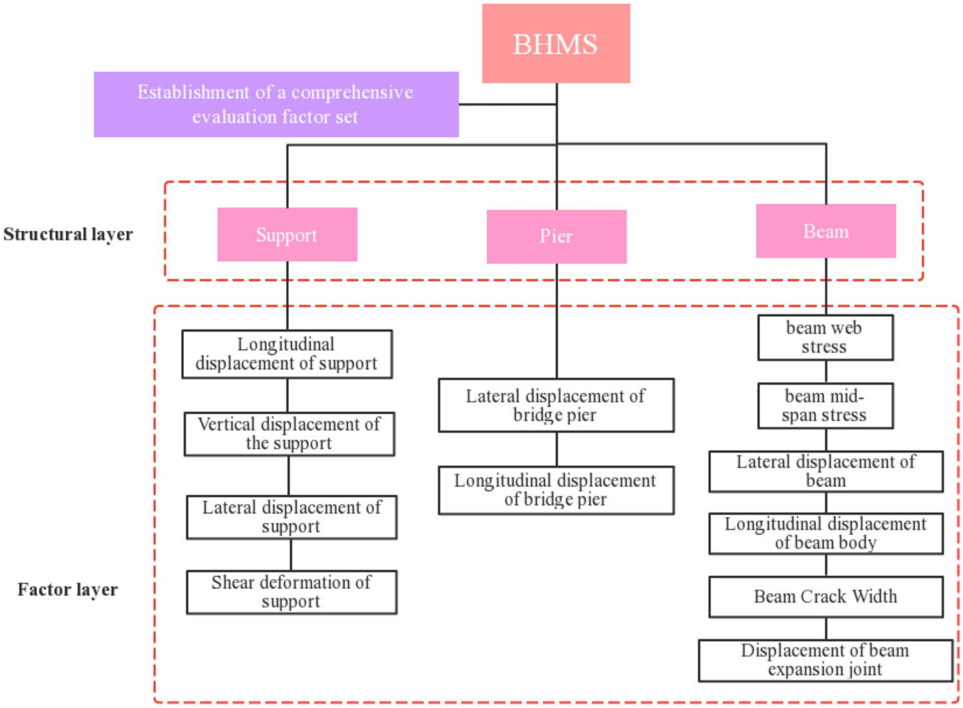


**Fig. 13** Establishment of a comprehensive evaluation factor set

measured value and the limit is brought into the membership function of the displacement, and the evaluation vector of the longitudinal displacement of the beam is $(0,0,0,1,0)^T$.

The three monitoring values of the beam mid-span stress are − 1.767 MPa, − 0.113 MPa, and 2.44 MPa. Bring them into the membership function of the pressure, respectively, and then find the average value of the three vectors, and get the evaluation vector of the beam mid-span stress as $(0.667,0,0,0,0.333)^T$.

The seven monitoring values of beam web stress are 1.157 MPa, 4.671 MPa, 1.741 MPa, 1.319 MPa, 1.086 MPa, 1.052 MPa, and 0.242 MPa. Bring them into the membership function of the stress, respectively, find the average value of 7 vectors, and get the evaluation vector of the beam web stress as $(0.143,0,0.486,0.127,0.244)^T$.

The monitored values of the maximum width of the cracks in the two beams are 0.555 mm and 1.84 mm respectively. Bring them into the membership function of the crack width, and then find the average of the two vectors, and get the evaluation vector of the beam crack width as $(0,0,0,0.5,0.5)^T$.

Combining the above five evaluation vectors, the secondary fuzzy relationship matrix of the beam body is obtained as Eq. (20):

$$R_1 = \begin{bmatrix} 0.667 & 0.143 & 0.467 & 0 & 0 \\ 0 & 0 & 0.533 & 0 & 0 \\ 0 & 0.486 & 0 & 0 & 0 \\ 0 & 0.127 & 0 & 1 & 0.5 \\ 0.333 & 0.244 & 0 & 0 & 0.5 \end{bmatrix}. \tag{20}$$

### 5.1.2 Single-factor analysis of bridge bearing

The longitudinal displacement of the bridge bearing is − 2.44 mm, and its displacement limit is 5 mm. The ratio of the measured value to the limit value is brought into the membership function of the displacement, and the evaluation vector of the longitudinal displacement of the bridge bearing is $(0,0,0.56,0.44,0)^T$.

The lateral displacement of the bridge bearing is 0.59 mm, and its displacement limit is 2 mm. The ratio of the measured value and the limit value is brought into the membership function of the displacement, and the evaluation vector of the lateral displacement of the bridge bearing is $(0,0.542,0.458,0,0)^T$.

The vertical displacement of the bridge bearing is 0.011 mm, and the displacement limit is 1.8 mm. The ratio of the measured value and the limit value is brought into the membership function of the displacement, and the evaluation vector of the vertical displacement of the bridge bearing is $(1,0,0,0,0)^T$.

The shear deformation of the bridge bearing is 0.076, and its displacement limit is 0.45. The ratio of the measured value and the limit value is brought into the membership function of the displacement, and the evaluation vector of the shear deformation of the bridge bearing is $(0,1,0,0,0)^T$ [22, 23].

Combining the above four evaluation vectors, the secondary fuzzy relationship matrix of the bridge bearing is obtained as Eq. (21):

$$R_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0.542 & 0 & 1 \\ 0.56 & 0.458 & 0 & 0 \\ 0.44 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}. \tag{21}$$

### 5.1.3 Single-factor evaluation of bridge piers

The longitudinal displacement of the pier is 0.376 mm, and its displacement limit is 27 mm. The ratio of the measured value to the limit value is brought into the membership function of the displacement, and the evaluation vector of the longitudinal displacement of the pier is $(1,0,0,0,0)^T$ [24].

The lateral displacement of the pier is 0.285 mm, and its displacement limit is 22 mm. The ratio of the measured value and the limit value is brought into the membership function of the displacement, and the evaluation vector of the lateral displacement of the pier is obtained as $(1,0,0,0,0)^T$.

Combining the above two evaluation vectors, the second-level fuzzy relationship matrix of the pier is obtained as Eq. (22):

$$R_3 = \begin{bmatrix} 1 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}. \tag{22}$$

### 5.1.4 Find the first-level fuzzy relationship matrix

The second-level fuzzy relationship matrix $R_i$ of the factors mentioned above is multiplied by its weight vector $W_i$, and the second-level evaluation result of a single factor can be obtained. As Eqs. (23)–(25):

$$B_1 = R_1 \cdot W_1 = \begin{bmatrix} 0.667 & 0.143 & 0.467 & 0 & 0 \\ 0 & 0 & 0.533 & 0 & 0 \\ 0 & 0.486 & 0 & 0 & 0 \\ 0 & 0.127 & 0 & 1 & 0.5 \\ 0.333 & 0.244 & 0 & 0 & 0.5 \end{bmatrix} \cdot \begin{bmatrix} 0.153 \\ 0.224 \\ 0.077 \\ 0.077 \\ 0.469 \end{bmatrix} = \begin{bmatrix} 0.170 \\ 0.041 \\ 0.109 \\ 0.340 \\ 0.340 \end{bmatrix} \tag{23}$$

$$B_2 = R_2 \cdot W_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0.542 & 0 & 1 \\ 0.56 & 0.458 & 0 & 0 \\ 0.44 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0.3 \\ 0.3 \\ 0.3 \\ 0.1 \end{bmatrix} = \begin{bmatrix} 0.3 \\ 0.262 \\ 0.306 \\ 0.132 \\ 0 \end{bmatrix} \tag{24}$$

$$B_3 = R_3 \cdot W_3 = \begin{bmatrix} 1 & 1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{25}$$

The second-level evaluation results of each factor are formed into a new matrix, which is the first-level fuzzy relationship matrix $R$. As Eq. (26)

$$R = [B_1\, B_2\, B_3] = \begin{bmatrix} 0.170 & 0.3 & 1 \\ 0.041 & 0.262 & 0 \\ 0.109 & 0.306 & 0 \\ 0.340 & 0.132 & 0 \\ 0.340 & 0 & 0 \end{bmatrix}. \tag{26}$$

#### 5.1.5 Result vector analysis

The first-level fuzzy relationship matrix $R$ is multiplied by the weight vector $W$ of the structure layer to obtain the evaluation result vector $B$, as Eq. (27):

$$B = R \cdot W = \begin{bmatrix} 0.170 & 0.3 & 1 \\ 0.041 & 0.262 & 0 \\ 0.109 & 0.306 & 0 \\ 0.340 & 0.132 & 0 \\ 0.340 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0.584 \\ 0.333 \\ 0.083 \end{bmatrix} = \begin{bmatrix} 0.282 \\ 0.111 \\ 0.165 \\ 0.243 \\ 0.199 \end{bmatrix}. \tag{27}$$

When the principle of maximum membership is used to evaluate the result vector, the result obtained is level 1 of bridge safety. When the closeness method is used to analyze the obtained evaluation results, the closeness algorithm given by Eq. (3) is used. The closeness of the fuzzy comprehensive evaluation result vector B calculated by this algorithm to each feature fuzzy subset is:

$$N(B, D_1) = N(B^{(1)}, D_1) = 0.8867$$

$$N(B, D_2) = N(B^{(2)}, D_1) = 0.8696$$

$$N(B, D_3) = N(B^{(3)}, D_1) = 0.8698$$

$$N(B, D_4) = N(B^{(4)}, D_1) = 0.8820$$

$$N(B, D_5) = N(B^{(5)}, D_1) = 0.8787.$$

The calculation results $N(B, D_1)$ can be found to be the largest through the calculation results. Therefore, the evaluation result and the fuzzy feature subset $(1{,}0{,}0{,}0{,}0)^{\mathrm{T}}$ are the closest to the evaluation result, and the result is that the structural safety level is level 1.

When the weight analysis method is used to evaluate the result vector, The calculation result is as Eq. (28):

$$n = \frac{0.282^2 \times 95 + 0.111^2 \times 80 + 0.165^2 \times 60 + 0.243^2 \times 40 + 0.199^2 \times 15}{0.282^2 + 0.111^2 + 0.165^2 + 0.243^2 + 0.199^2} = 60.38. \tag{28}$$

The evaluation score obtained is 60.38, and the score obtained is brought into the evaluation score interval Table 1. It can be seen that the safety level of this continuous girder bridge is three. Through the analysis of the result vector, the measurement item data corresponding to level 1 of safety is not large, and it is close to the data corresponding to level 5. Therefore, it is too optimistic about evaluating its security level as level 1. It is reasonable to use the weight analysis method to define the safety level of the continuous girder bridge as level 3.

### 5.2 Expanded application of BHMS

#### 5.2.1 Daily and monthly safety assessment of continuous girder bridges

Using the FCEM, continuously calculate the safety score of the continuous girder bridges for 24 h, and the score change is shown in Fig. 14. Using the same method to calculate the safety score of the continuous girder bridge throughout July of 2016, the score changes are shown in Fig. 15. It can be seen from Fig. 14 that in 1 day, the safety score of continuous girder bridges is maintained within the range of 50–70, and the safety assessment level is maintained at level 3. In one month, the structural safety level of the bridge is level 3 most of the time, and the overall safety level varies between level 2 and level 3.

According to the contents of "Beijing Metro Line 5 Civil Engineering Facilities Inspection" and "Beijing Metro Line 5 Elevation Benchmark and Bridge Pier Displacement Monitoring Report", the continuous girder bridges of piers 14–17 have severe deterioration of the plate rubber bearings, and there are two long-lasting cracks in the webs of the side span beams. Prestressed concrete has water seepage and whitening, and local concrete peels off. The vertical displacement

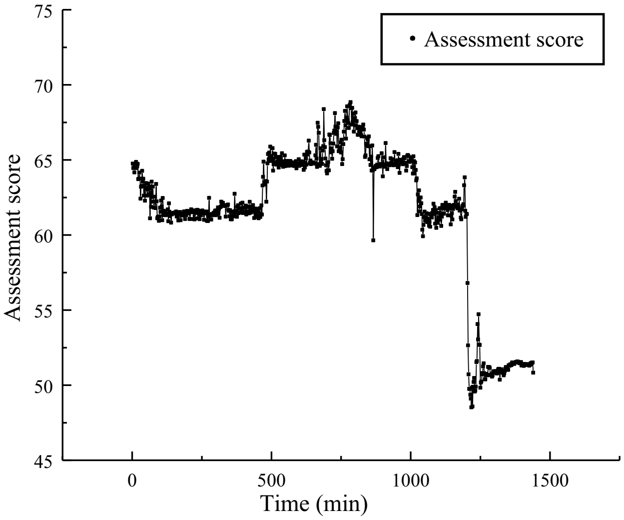


**Fig. 14** Changes in the 24-h safety assessment scores of continuous beam bridges

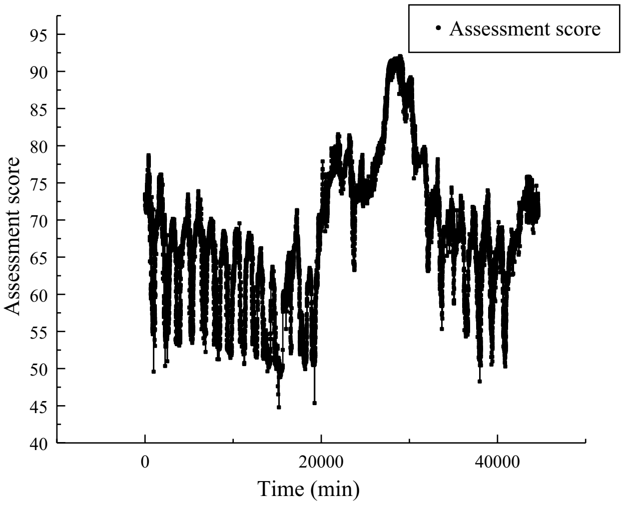


**Fig. 15** Changes in safety assessment scores of continuous girder bridges in July 2016

difference between the monitoring piers is close to the warning value, and attention should be paid. The assessment result of the safety status of the bridge is level 3, and the assessment result is similar to that obtained by the FCEM. It shows that the SAM used in this paper applies to continuous girder bridges.

### 5.2.2 Daily and monthly safety assessment of simply supported girder bridge

The FCEM is used to calculate the safety score of the simply supported girder bridge for 24 h, and the score changes are shown in Fig. 16. Using the same method to calculate

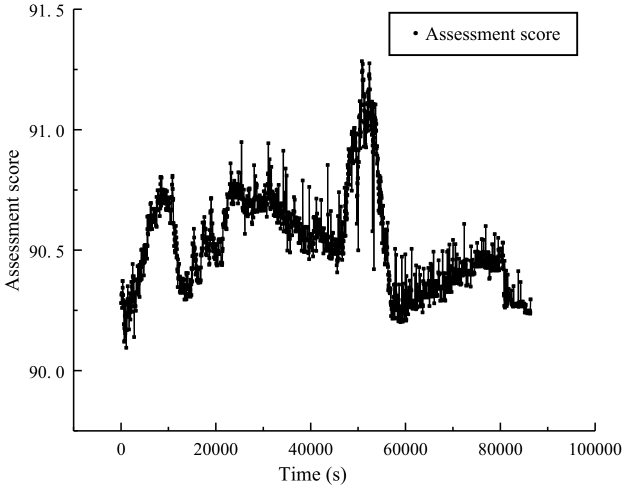


**Fig. 16** Changes in the 24-h safety assessment scores of simply supported beam bridges

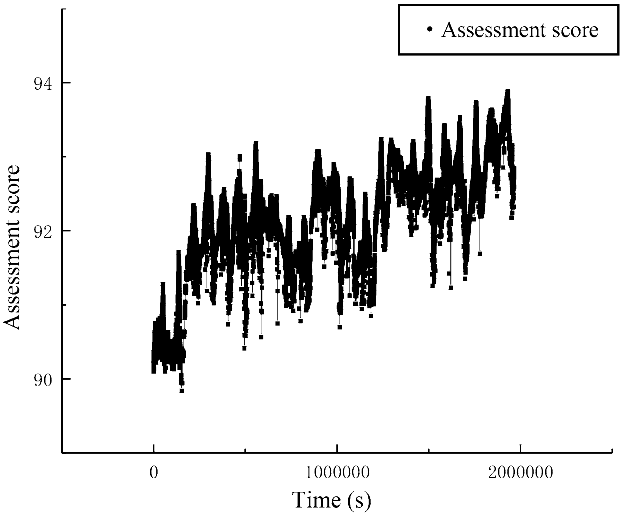


**Fig. 17** Changes in safety assessment scores of simply supported beam bridges in January 2016

the safety score of the simply supported girder bridge for the entire January of 2016, the score changes are shown in Fig. 17. It can be seen from Fig. 16. that in 1 day, the safety score of the simply supported girder bridge remained stable at over 90 points, and the safety assessment level was level 1. In one month, the safety score of the bridge fluctuates mainly between 90 and 94, and the structural safety grade is level 1.

According to the contents of "Beijing Metro Line 5 Civil Engineering Facilities Inspection" and "Beijing Metro Line 5 Elevation Benchmark and Bridge Pier Displacement Monitoring Report", the slab rubber bearing of the simply supported girder bridge with piers between 119 and 120 has slightly deteriorated, and there are no other diseases. The vertical displacement difference between the monitored piers

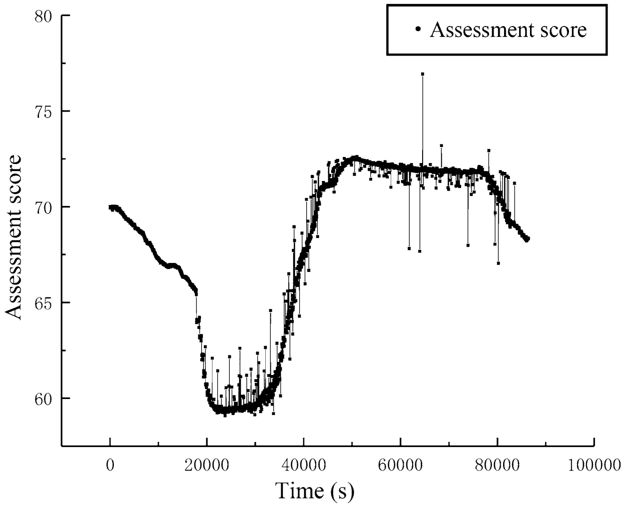


**Fig. 18** Changes in the 24-h safety assessment scores of steel–concrete composite beam bridges

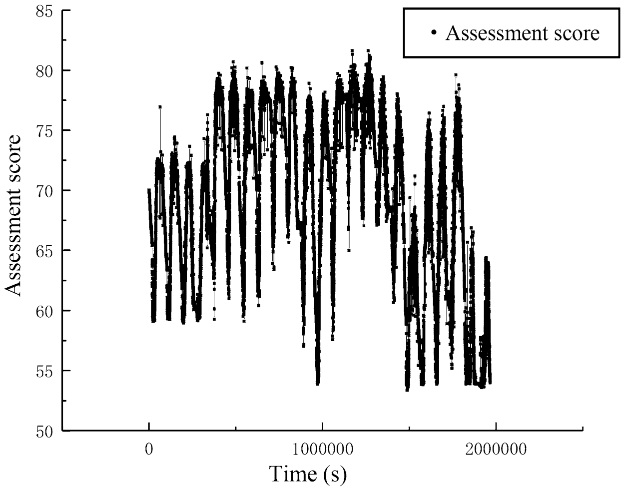


**Fig. 19** Changes in safety assessment scores of steel–concrete composite girder bridges in January 2016

is less than the safe value. The assessment result of the safety status of the bridge is level 1. The evaluation result of the bridge inspection report is similar to the result obtained by the FCEM, indicating that the safety evaluation method used in this paper applies to a simply supported girder bridge.

### 5.2.3 Daily and monthly safety assessment of steel–concrete composite girder bridge

The FCEM is used to calculate the safety score of the steel–concrete composite girder bridge for 24 h. The score changes are shown in Fig. 18. At the same time, the safety score for the entire January of 2016 is calculated, and the score changes are shown in Fig. 19. It can be seen from Fig. 18. that in 1 day, the safety score of the steel–concrete composite girder bridge is roughly maintained within the interval of 60–75, and the safety assessment level varies between level 2 and level 3. In 1 month, the evaluation score of the steel–concrete composite girder bridge fluctuates between 50 and 80, and the structural safety level varies from level 2 to level 3.

According to the content of "Beijing Metro Line 5 Civil Engineering Facilities Inspection" and "Beijing Metro Line 5 Elevation Benchmark and Bridge Pier Displacement Monitoring Report", the steel box girder of the steel–concrete composite girder bridge of the 183–186 pier section is slightly corroded. The steel–concrete mixed box girder wing plate seeps and sees white, and the corner of the wing plate and the web Whitening. The vertical displacement difference between the monitored piers is less than the safe value. The assessment result of the safety status of the bridge is level 2. Since the previous bridge inspection report mainly counted the apparent disease of the bridge, it did not evaluate factors such as the horizontal displacement of the beam. However, the measured horizontal displacement of the steel–concrete composite beam, including the horizontal displacement of the beam body and the horizontal displacement of the bridge pier, has the problem of approaching the limit or exceeding the limit. Therefore, it is acceptable that the results obtained using the bridge SAM proposed in this paper are partially different from the measured results.

## 5.3 Summary

The comparative data analysis of the above three bridges shows that the bridge structure SAM based on real-time monitoring data proposed in this paper mainly aims at the safety assessment of small and medium-sized bridge structures. The method has strong applicability, especially in evaluating supported girder bridges. The reason is that the trainload and temperature have little effect on the structural deformation of simply supported girder bridges compared to continuous girder bridges and composite girder bridges, so the scores are relatively stable. For continuous girder bridges and composite girder bridges, especially composite girder bridges, the structural deformation is significant under the action of train load and temperature, and the displacement limit specified in the code is also much larger than that of supported girder bridges. This significantly fluctuates in the safety assessment results, derived from Figs. 14 and 18.

However, this fluctuation does not affect the use of the evaluation method in composite and continuous girder bridges. This can be seen from the single-month assessment results of three bridges in the Beijing subway. The evaluation scores of supported girder bridges in a single month are all within the first-class range, showing no structural safety problem for simply-supported girder bridges, and the structure can be undisputedly rated as first-class. At the same time, the continuous girder bridge and the composite girder bridge in a single month, although the evaluation scores fluctuate significantly, the overall score is still maintained in the second and third grades. The safety level of the bridge can be determined entirely by the evaluation score combined with the actual situation of the bridge. This does not deny the applicability of the method, but the safety level of the bridge structure cannot be directly determined by the evaluation method alone.

## 6 Conclusion and outlook

In this paper, through an in-depth study of the structural SAM in the bridge health monitoring system, the following conclusions are drawn:

1. A set of SAM suitable for modern small and medium bridge structures has been established. This method can comprehensively consider all the factors that affect the safety assessment of the bridge structure and vectorize all aspects through the membership function. At the same time, combined with the two-level FCEM, the final safety evaluation vector of the bridge structure was given. The weight is determined through expert discussion to quantify the result vector accurately. Finally, combined with the final quantitative value, the classification assessment of the safety state of the bridge structure is completed.
2. Combined with the Beijing Metro Line 5 project, the $3 \times 30$ m continuous girder bridge, simply supported girder bridge, and steel–concrete composite girder bridge are used for 24-h safety evaluation verification using the structural SAM proposed in this paper. The verification result is compared with the actual test report to verify the accuracy of the application of the SAM in the BHMS.

The structural SAM established in this paper, combined with data prediction technology, can form a complete set of bridge health monitoring and early warning models. The prediction based on the BHMS data needs to be studied in depth in current practice. Based on the current development trend of bridges at home and abroad, the research and development of bridge health monitoring and early warning systems is the general trend, requiring more attention from researchers.

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## References

1. Muhammad RS, Park JW, Lee JH et al (2020) Instant bridge visual inspection using an unmanned aerial vehicle by image capturing and geo-tagging system and deep convolutional neural network. Struct Health Monit 07:1–18. https://doi.org/10.1177/1475921720932384
2. Sung YC, Takaaki M, Lin TK et al (2012) A case study on bridge health monitoring using position-sensitive detector technology. Struct Control Health Monit 19:295–308. https://doi.org/10.1002/stc.436
3. Mei QP, Mustafa G (2018) A crowdsourcing-based methodology using smartphones for bridge health monitoring. Struct Health Monit 12:1–18. https://doi.org/10.1177/1475921718815457
4. Wang YX (2019) Development and application of toolbox for optimal placement of measuring points in long-span bridge structure health monitoring system. Dalian University of Technology, Liaoning
5. Sun LM, Shang ZQ, Xia Y (2019) Research status and prospects of bridge structural health monitoring under the background of big data. China J Highw Transp 32(11):1–20. https://doi.org/10.19721/j.cnki.1001-7372.2019.11.001
6. Xu MM (2018) Research on fault diagnosis of bridge health monitoring sensor based on deep learning. Chongqing Jiaotong University, Chongqing
7. Wu LQ, Zhang LL (2020) Bridge structure health detection based on data mining technology. J Jilin Univ (Engineering Science Edition) 50(2):565–571. https://doi.org/10.13229/j.cnki.jdxbgxb20190083
8. Agdas DR, Jennifer A, Martinez JR et al (2015) Comparison of visual inspection and structural-health monitoring as bridge condition assessment methods. J Perform Constr Facil. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000802
9. Cappello C, Zonta D, Pozzi M et al (2015) Impact of prior perception on bridge health diagnosis. J Civil Struct Health Monit. 5:509–525. https://doi.org/10.1007/s13349-015-0120-0
10. Li SL, Jinping Ou JP, Wang JB et al (2018) Level 2 safety evaluation of concrete-filled steel tubular arch bridges incorporating structural health monitoring and inspection information based on China bridge standards. Struct Control Health Monit 08(24):1–20. https://doi.org/10.1002/stc.2303
11. Zhao XY, Yang YW (2011) Health inspection system of bridge and tunnel structure of urban railway transit based on RFID technology. Adv Mater Res 2(211–212):871–875. https://doi.org/10.4028/www.scientific.net/AMR.211-212.871
12. Farhey DN (2016) Instrumentation system performance for long-term bridge health monitoring. Struct Health Monit 5(2):0143–0211. https://doi.org/10.1177/1475921706057986
13. Yuan C (2018) Research on the optimal placement method of bridge health monitoring sensors based on deep learning. Chongqing Jiaotong University, Chongqing

14. Zhao JJ, He YH, Huang RQ et al (2015) Slope stability evaluation index weight based on a factor analysis method. J Southwest Jiaotong Univ 2:325–330. https://doi.org/10.3969/j.issn.0258-2724.2015.02.018
15. Zhang BY (2018) Research on optimal arrangement and damage identification of long-span bridge health monitoring sensors. Wuhan University of Technology, Hubei
16. Rahmatalla S, Hudson K, Liu Y et al (2014) Finite element modal analysis and vibration waveforms in health inspection of old bridges. Finite Elem Anal Des 78:40–46. https://doi.org/10.1016/j.finel.2013.09.006
17. Wang XG, Fu MF, Hu XR (2015) Boundary surface model based on membership function under cyclic loading. J Harbin Eng Univ 12:1560–1564. https://doi.org/10.11990/jheu.201409017
18. Dorafshan S, Maguire M (2018) Bridge inspection: human performance, unmanned aerial systems, and automation. J Civ Struct Health Monit. https://doi.org/10.1007/s13349-018-0285-4
19. Technical Specifications of Maintenance for Highway Tunnel. China Communications Press. (JTG H12-2015)
20. Rules for the repair of bridges and tunnels in general-speed railway. China Railway Press. (TG/GW103-2018)
21. Interim Code for Design of Railway Bridges and Culverts by Limit State Method. China Railway Press. (Q/CR 9300-2014)
22. Deterioration assessment standards for railway bridges and tunnels. China Railway Press. (TB/T 2820.1~2820.8-1997)
23. Code for rating existing railway bridges. China Railway Press. (Rail Transport Letter [2004] No. 120)
24. Metro Design Code. China Construction Industry Press. (GB50157-2013)