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Comprehensive assessment of cable-stayed bridge based on Pagerank algorithm

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Abstract

This paper develops an improved structural health assessment method for cable-stayed bridge to address the issue of neglecting component correlations in existing assessment standards. Firstly, the directed graph of fault transmission between components in the cable-stayed bridge system was constructed. The Pagerank algorithm was used to analyze the degree of correlation between these components, and then the influencing degree of and the influenced degree of each component were determined. Secondly, considering the failure rate of individual components and the influenced degree of other component faults, a condition evaluation method with component correlation for cable-stayed bridge was proposed. Finally, the improved assessment method was applied to a super large-span steel cable-stayed bridge as a case study and compared with the relevant assessment specifications. The results show that main girder alignment, cable force and main tower alignment have a greater degree of correlation with other components and are important indicators for bridge health monitoring. Visual inspection of main girder and bridge bearing are the fault appearance components and should be paid attention to in preventive maintenance. The drainage system and electromechanical facilities are the fault source components and must be kept in good condition in daily inspections. The proposed method considers the interrelationships among components more comprehensively and can provide more reliable bridge health assessment results to support bridge maintenance decisions.

Keywords: Cable-stayed bridge, Assessment method, Component correlation, Pagerank algorithm, Defect propagation

1 Introduction

The cable-stayed bridge represents a significant form of modern bridge engineering. Currently, China holds the highest number of cable-stayed bridge (Pang et al. 2022). However, with the increasing service life of cable-stayed bridge, environmental erosion and repeated loading can easily lead to aging and damage of materials and components, potentially resulting in catastrophic bridge accidents (Li and Feng 2023). Therefore, conducting timely and accurate assessments and maintenance for cable-stayed bridge is of utmost importance. Currently, in engineering practice, the assessment of cable-stayed bridge status largely relies on normative methods (JTG/T 3365-01-2020, 2020; JTG/T H21-2011, 2011). This method is based on the Analytic Hierarchy Process (AHP), known for its well-defined metrics and ease of application, and has therefore found widespread use. However, this approach has its shortcomings, including subjectivity and a lack of consideration for interrelationships among metrics (Yang et al. 2019). To solve these problems, scholars have proposed various methods aimed at mitigating subjective biases.

Some scholars have introduced methods such as Fuzzy Analytic Hierarchy Process (Jakiel and Fabianowski 2015), neural networks (Gai et al. 2023), and reliability theory assessment (Raizer 2004) to reduce subjective biases. Others have employed evidence reasoning theory (Bolar et al. 2013) to handle redundant or conflicting information between manual inspection and health monitoring data.

Zong et al. introduced a fuzzy evaluation method that constructs a three-level logical evaluation structure with 21 basic influencing factors using the Analytic Hierarchy Process. They used the Delphi method to determine the weights of each judgment matrix, providing theoretical support for the assessment of large-span steel bridge (Zong et al. 2021). Yang et al. proposed a novel comprehensive condition assessment method based on Improved Interval Evidence Theory (IIET), Fuzzy Analytic Hierarchy Process (AHP), and natural fusion. They applied this method to evaluate a three-span PSC continuous box girder bridge, demonstrating its advantages over existing AHP assessment methods and traditional combination methods (Yang et al. 2019). Moufti et al. put forth a Fuzzy Evidence Hierarchy Reasoning method, systematically processing and aggregating detected bridge defect measurements, establishing an enhanced reliable bridge assessment platform for detailed condition assessment of concrete bridge under uncertain conditions (Moufti et al. 2014). Wang et al. introduced the use of Evidence Reasoning (ER) methods to model the inherent uncertainty in bridge subjective assessments and aggregate assessments of bridge components, offering a comprehensive evaluation of bridge condition (Wang and Elhag 2008).

However, cable-stayed bridge represents high-order hyperstatic composite structure. It possesses characteristics such as complex stress distribution (Kildashti et al. 2020) and strong intercomponent correlation. For example, damage to stay cables can affect cable tension and main girder deflection (Tian et al. 2021). The cable forces in cable-stayed bridge control internal force distribution and bridge deformations (Huang et al. 2018). Moreover, auxiliary piers have an impact on the structural response of cable-stayed bridge (Wei et al. 2020). Currently, existing assessment methods do not account for the intricate correlations among components in cable-stayed bridge. These methods have also failed to demonstrate the interdependencies among individual components.

In the field of engineering fault diagnosis, extensive research has delved into component correlations. Typically, the Pagerank algorithm is employed for analysis (Shen et al. 2019; Zhang et al. 2019) (Deng et al. 2023, Huang et al. 2023) to gain a deeper understanding of these associations. This algorithm is known for its simplicity and computational efficiency, enabling the ranking of component importance.

Wang et al. proposed a time-series data mining and forecasting strategy based on information causality and the Pagerank algorithm. This strategy was applied to study the interaction between hydraulic, mechanical, and electromagnetic factors in a hydraulic power generation system with frequent changes in operating conditions

(Wang et al. 2023). Su et al. introduced a method based on the Pagerank algorithm to rapidly and accurately identify critical nodes in power systems, and they validated this method using the IEEE 39-node system (Su et al. 2021). Zhu et al. relying on the Pagerank algorithm and resource iteration concept, proposed the Improved Pagerank Algorithm (IPRA) to identify influential process nodes. Comparative analyses with existing algorithms demonstrated that this method excels in identifying influential nodes in complex production networks (Zhu et al. 2023).

Therefore, the objective of this paper is to apply the Pagerank algorithm to propose an improved method for assessing the condition of a cable-stayed bridge. Based on the Pagerank algorithm to calculate the correlation between the components of a cable-stayed bridge, the degree of influence and the degree of being influenced between the indexes are derived and verified with an actual cable-stayed bridge as a case study. This method intends to remedy the problem of component correlation, which is neglected in the existing assessment methods, so as to assess the condition of a cable-stayed bridge more accurately.

2 Correlation analysis method for components

The Pagerank algorithm is a search engine algorithm established by Sergey Brin and Larry Page, the two founders of Google. The algorithm relates the ranking of web pages to a number of factors related to the web page (Brin and Page 1998). The main principle of the PageRank algorithm is that if page A is able to link to page B, then it is assumed that page A passes an importance value (PR value) to page B. Based on the linking relationship, this value is calculated iteratively until it is smooth and is calculated as shown in Eq. (1).

$$D_{PR}(P) = \frac{(1-d)}{N} + d\sum_{i=1}^{n} \frac{D_{PR}(T_i)}{N_{T_i}} \tag{1}$$

where $D_{PR}(P)$ is the PageRank value of a webpage, d is the damping factor, taking the value of $0 < d < 1$, there is a damping factor because not all users will browse along the hyperlinks of the webpage, generally take $d = 0.85$; N is the number of all pages; T_1, T_2, $\cdots T_n$ is the webpage pointing to the webpage P; $D_{PR}(P)$ is the webpage T_i pointing to the webpage P has a PageRank value; N_{T_i} is the webpage T_i has the number of export links.

Based on this principle, the interactions between the components of a cable-stayed bridge can be viewed as the interlinking of pages in the Internet, with failures passing along the relational path. By analyzing the correlation degree of fault degradation among the components of the cable-stayed bridge, it can provide reliable data for the subsequent scoring. The PR value represents the degree of influence of one component on another component. The higher the value, the greater the impact and correlation of the component on other components.

Based on the above idea, a directed graph of fault transmission among the components of the cable-stayed bridge is established. Based on the Pagerank algorithm, the inter-component correlation is solved by iterative calculation of the probability transfer matrix, as in Eq. (2) (Brin and Page 1998). Figure 1 shows the flow of the algorithm implementation.

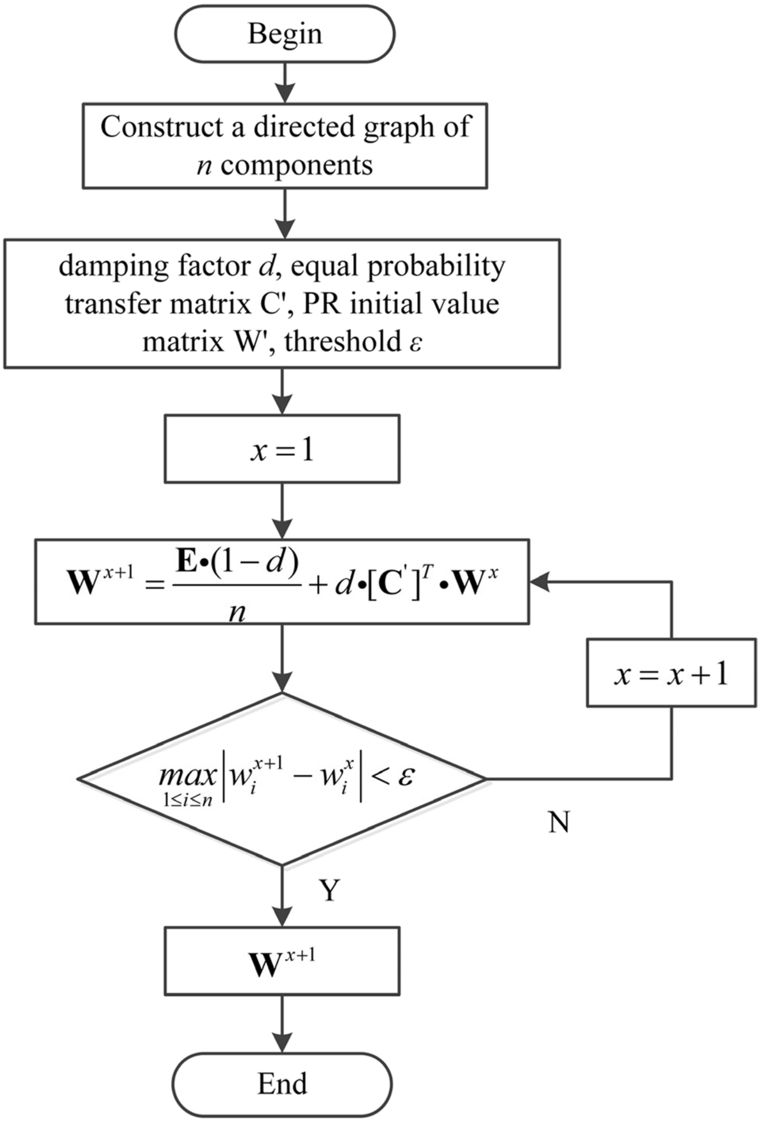


Fig. 1 Pagerank algorithm implementation process

$$W^{x+1}=\frac{E\cdot(1-d)}{n}+d\cdot\left[C'\right]^T\cdot W^x \tag{2}$$

Where E is the $(n\times 1)$ order matrix whose elements are all 1, n is the number of system components, d is the damping factor, which is selected as 0.3 with reference to the related literature (Long et al. 2017), C' is the equal probability transfer matrix, and the initial PR value of each node is W', and W^{x+1} denotes the $(n\times 1)$ order matrix composed of the importance degree of each node obtained from the $(x+1)$ iteration.

The correlation between components of cable-stayed bridge is divided into the degree of influence C_I and the degree of being influenced C_K. C_K represents the degree of probability that a component is affected by the transmission of faults from other components and fails, and C_I represents the probability that a component will have an influence on other components. In this paper, with the help of the Pagerank algorithm and with reference to Eq. (2), we obtain iterative formulas for the calculation of the value of C_K and C_I.

$$C_K^{x+1} = \frac{E\cdot(1-d)}{n} + d\cdot\left[C'\right]^T\cdot C_K^x \tag{3}$$

$$C_I^{x+1} = \frac{E\cdot(1-d)}{n} + d\cdot\left[\left[C^T\right]'\right]^T\cdot C_I^x \tag{4}$$

In this paper, the power method is used to solve the C_K and C_I values. Generally, the initial value of PageRank (PR) does not significantly impact the convergence of the final PR value and the ultimate ranking. As a common practice, the initial values for C_K and C_I are usually set as a matrix with $(n \times 1)$ elements, all equal to 1.

3 Comprehensive assessment method for cable-stayed bridge based on Pagerank algorithm

Based on the foundation of previous research (Liu et al. 2017a), this paper proposes a common method of dividing first-level indicators, which is categorized according to the perspective of the main components. Therefore, this paper integrates the manual inspection and health monitoring data, constructs the corresponding evaluation index system, and assigns the weights, which is shown in Fig. 2.

There is a correlation between the components in the overall cable-stayed bridge system. This leads to a combined failure rate of the components of the cable-stayed bridge that consists of two aspects. First, the components themselves may fail, generating a corresponding failure rate. Secondly, due to the correlation of failures between components, this may lead to the propagation of failures, which may result in failures of other components. As a result, the overall cable-stayed bridge failure rate may increase when component correlations are taken into account compared to the case of individual failures, and therefore the scoring results obtained may be lower. We introduce the concept of a method for calculating the independent failure rate of equipment components into the

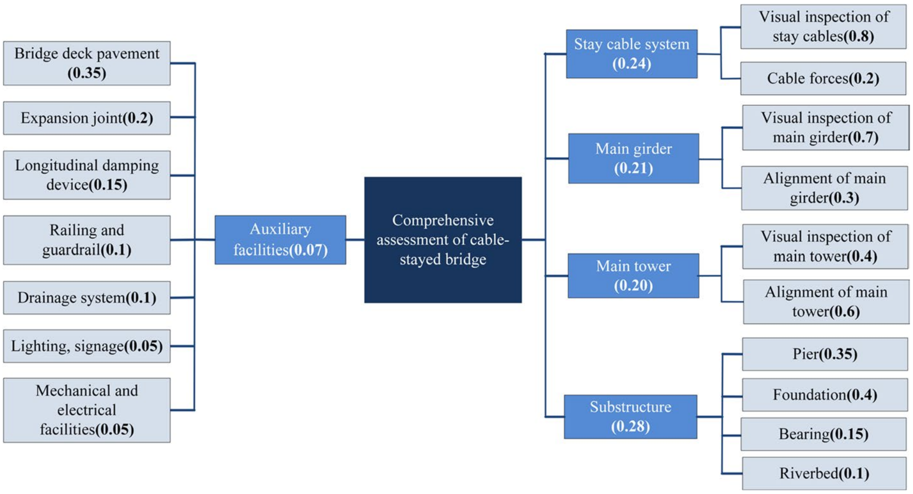


Fig. 2 Comprehensive assessment index system for the condition of cable-stayed bridge

condition assessment of cable-stayed bridge (Long et al. 2017). The component scoring result considering correlation can be expressed as the component-independent failure scoring result minus the failure effects of other components on it, as described below.

Assuming that the considered relevance score of each component V_i is S_{ii}, and the result of the separate failure score is S_i, the failure rate impact of other components on V_i, denoted by $O_i \times S_{i-}$.Where O_i is the probability that component V_i is affected by the failure of other components, i.e., the corresponding C_K value, and is the value of the demerit points of the components that have relevance to it other than component $V_{i.}$ Finally, the following expression can be obtained:

$$S_{ii} = S_i - O_i \times S_{i-} \tag{5}$$

Finally, based on the score S_{ii} of each component, the final level 1 index and the overall score of the bridge are obtained according to the corresponding weight allocation.

4 Case study

4.1 Background information of bridges

This article takes the inspection data of a large span steel cable-stayed bridge in Jiangsu Province, China as an example, and evaluates it using the method of considering component correlation. The main bridge has a total length of 1288 m and is a steel tower and box girder structure. The entire bridge steel structure is made of Q345D steel. The cables are arranged symmetrically on the east and west sides, using 7 mm galvanized high-strength low relaxation steel wire. The bridge was officially completed and opened to traffic in 2005.

During the inspection of the background bridge in 2013, some important structural issues were identified (Liu et al. 2017b), as shown in Fig. 3. In the cable system, the main types of diseases include the detachment of anti-rust paint on the steel casing of the cable, accounting for approximately 16.1% of the total diseases. In addition, there are also issues such as coating deterioration and anti-corrosion oil leakage. For the steel box girder, there are multiple problems such as rust, oil leakage, and paint peeling at the

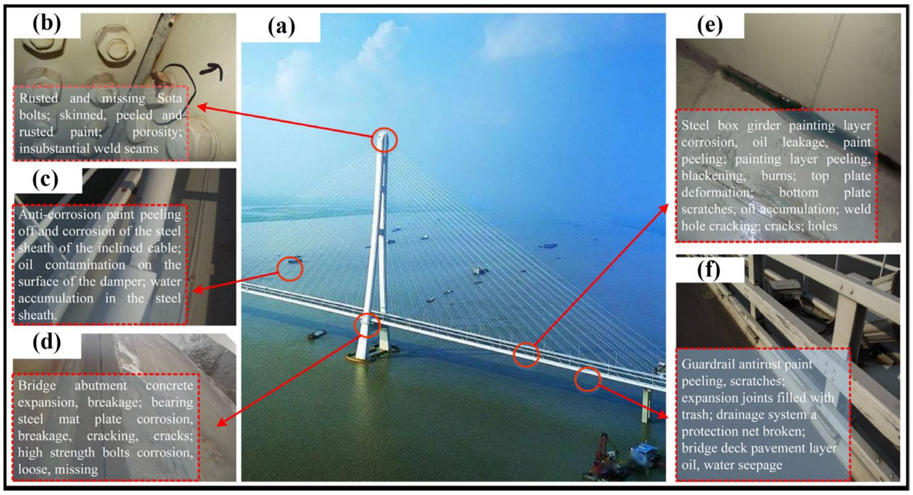


Fig. 3 Disease situation of a cable-stayed bridge

internal joints of the coating layer, among which the longest rust length of the coating layer is 3.0 m. In the truss structure of the main girder, common problems include welding hole cracking, cracks, holes, scratches, etc. Among them, 73.6% of the box compartments have diagonal web member cracking problems. As for the cable tower, the main diseases are coating deterioration and bolt corrosion or loosening, which occur in 55.8% and 42.3% of the box compartments, respectively. In terms of the substructure, the support suffered damage to the pad stone concrete. Concrete expansion and cracking and other issues may occur locally on the bridge pier. In addition, in the ancillary facilities, issues such as peeling and scratching of anti-rust paint on guardrails, blockage of expansion joints, damage to a protective net in the drainage system, and two 5 m long longitudinal cracks on the bridge deck pavement layer have also been detected, with oil stains, water seepage, and other issues present in 0.16% of the area.

In addition, the monitoring of the cable force, main beam alignment, and cable tower alignment of the bridge was as follows: for cable force, the sum of upstream and downstream cable force tests was basically the same, and the unevenness did not exceed 2% of the total cable force on one side. The overall performance of the structural cable force was stable; The deflection of the main beam sank, and by October 2013, the mid span deflection had decreased by 80 mm. For the cable tower alignment, there was currently no abnormal deviation at the top of the tower.

4.2 Comprehensive evaluation process

4.2.1 Solution of correlation values among components

Considering the actual composition structure of the cable-stayed bridge system, we can construct a connection diagram between various components based on the Pagerank algorithm, as shown in Fig. 4. The connecting lines in Fig. 4 indicate which

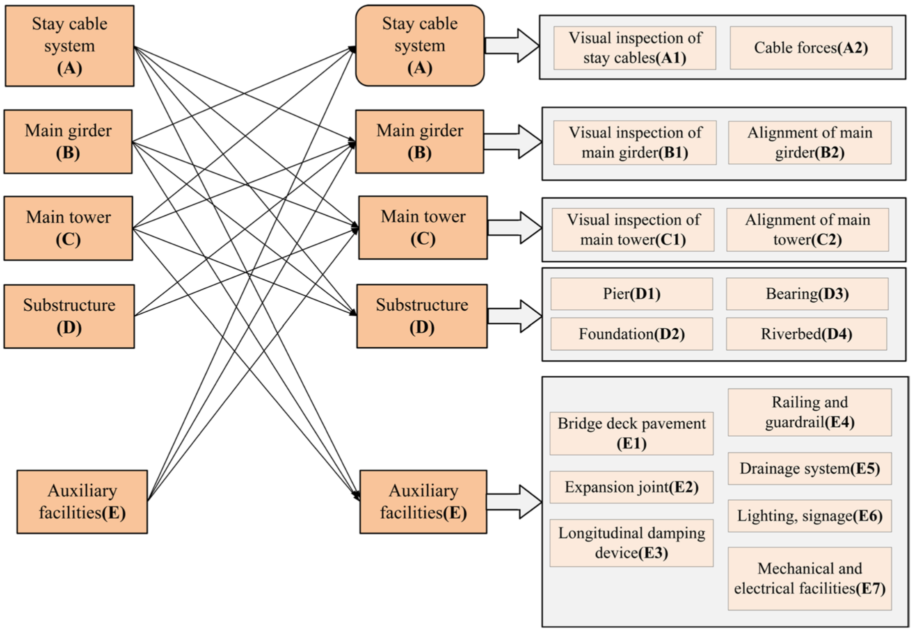


Fig. 4 Connection diagram of various components of cable-stayed bridge

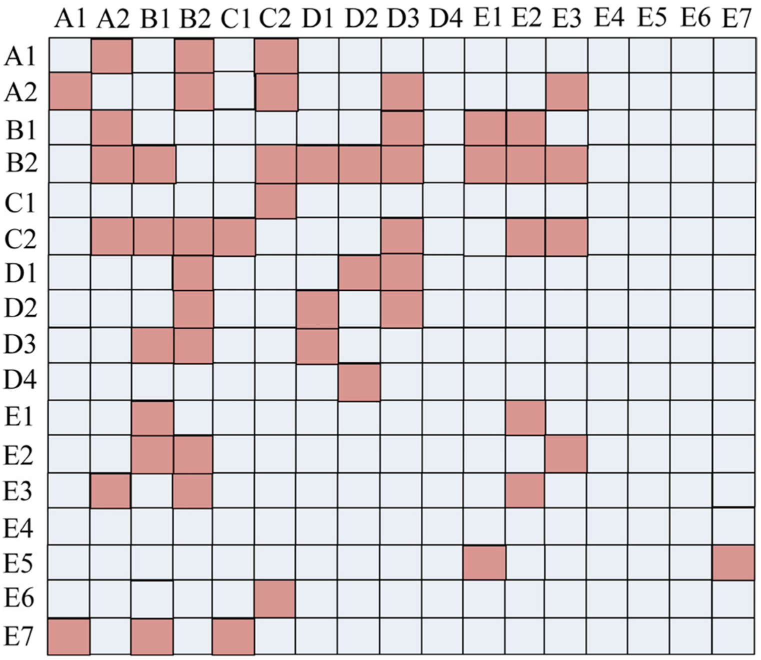
components of the tier 1 indicators are relevant, as well as the separate tier 2 indicators under the tier 1 indicators, which are numbered. Through expert consultation and structural stress characteristics, we analyzed the potential fault transmission relationships between various components of the bridge, and obtained a directed graph of fault transmission among various components of the cable-stayed bridge system, as shown in Fig. 5. The numbering in Fig. 5 corresponds to each component in Fig. 4, and the color of the squares shows the obvious expression of component correlation. The dark-colored squares in the figure represent that the horizontal coordinate component corresponding to the square has a certain correlation with the vertical coordinate component, on the contrary, the light-colored squares represent that the two components do not have obvious correlation. For a fault transmission directed graph with n nodes, its adjacency matrix C can be expressed as n × n matrix (Long et al. 2017):

When $i \neq j$:

$$C_{ij} = \begin{cases} 1, & \text{If there is an edge pointing from node i to node j} \\ 0, & \text{There is no edge pointing from node i to node j} \end{cases} \tag{6}$$

When $i = j$, $C_{ij} = 0$.

At the same time, the state equal probability transfer matrix can also be derived as in Eq. (7). Each row of the C' matrix represents a component, as does each column. If the corresponding element of each component is not zero, it means that there is some correlation between these components.



	A1	A2	B1	B2	C1	C2	D1	D2	D3	D4	E1	E2	E3	E4	E5	E6	E7
A1	⬜	🟥	⬜	🟥	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
A2	🟥	⬜	⬜	🟥	⬜	🟥	⬜	⬜	🟥	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜
B1	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	🟥	⬜	🟥	🟥	⬜	⬜	⬜	⬜	⬜
B2	⬜	🟥	🟥	⬜	⬜	🟥	🟥	🟥	🟥	⬜	🟥	🟥	🟥	⬜	⬜	⬜	⬜
C1	⬜	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
C2	⬜	🟥	🟥	🟥	🟥	⬜	⬜	⬜	🟥	⬜	⬜	🟥	🟥	⬜	⬜	⬜	⬜
D1	⬜	⬜	⬜	🟥	⬜	⬜	⬜	🟥	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
D2	⬜	⬜	⬜	🟥	⬜	⬜	🟥	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
D3	⬜	⬜	🟥	🟥	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
D4	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
E1	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜
E2	⬜	⬜	🟥	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜
E3	⬜	🟥	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜
E4	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
E5	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	🟥
E6	⬜	⬜	⬜	⬜	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
E7	🟥	⬜	🟥	⬜	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜

Fig. 5 Directed diagram of fault transmission among various components of cable-stayed bridge system

$$C' = \begin{pmatrix} 0 & 1/3 & 0 & 1/3 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/5 & 0 & 0 & 1/5 & 0 & 1/5 & 0 & 0 & 1/5 & 0 & 0 & 0 & 1/5 & 0 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 0 & 0 & 0 & 0 & 0 & 1/4 & 0 & 1/4 & 1/4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/9 & 1/9 & 0 & 0 & 1/9 & 1/9 & 1/9 & 1/9 & 0 & 1/9 & 1/9 & 1/9 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/7 & 1/7 & 1/7 & 1/7 & 0 & 0 & 0 & 1/7 & 0 & 0 & 1/7 & 1/7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/3 & 0 & 0 & 0 & 1/3 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/3 & 0 & 0 & 1/3 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/3 & 1/3 & 0 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/3 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/3 & 0 & 0 & 0 & 0 \\ 0 & 1/3 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/2 & 0 & 0 & 0 & 0 & 0 & 1/2 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/3 & 0 & 1/3 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \tag{7}$$

According to Eq. (3) and d is taken as 0.3 based on experience. The matrix iteration was performed. The C_K value was calculated using programming software. A correlation transformation on the adjacency matrix C was performed to obtain the transposed adjacency matrix C_T and its equal probability transition matrix $[C_T]$ ‘, as shown in Eq.8. According to Eq. (4), C_I values of each component was obtained.

Table 1 shows the C_K values and C_I values of each component. The influencing and influenced degree of the main girder alignment, cable force, and cable tower alignment are relatively large, indicating that these three indicators have a wide range of influence. Therefore, health monitoring of bridges is particularly important, especially the changes in these three monitoring indicators. For the visual inspection of the main girder and bearing, their C_K values are large, while the C_I values are small. They are most susceptible to other component failures and can easily reflect abnormal structural conditions

Table 1 C_K and C_I values of various components

Component name	Component number	Influenced degree C_K	Influencing degree C_I
Visual inspection of stay cables	A1	0.0505	0.0529
Cable forces	A2	**0.0757**	**0.0634**
Visual inspection of main girder	B1	**0.0736**	0.0552
Alignment of main girder	B2	**0.0850**	**0.0768**
Visual inspection of main tower	C1	0.0488	0.0462
Alignment of main tower	C2	**0.0682**	**0.0666**
Pier	D1	0.0571	0.0518
Foundation	D2	0.0621	0.0518
Bearing	D3	**0.0690**	0.0516
Riverbed	D4	0.0412	0.0464
Bridge deck pavement	E1	0.0557	0.0466
Expansion joint	E2	0.0667	0.0502
Longitudinal damping device	E3	0.0581	0.0509
Railing and guardrail	E4	0.0412	0.0412
Drainage system	E5	0.0412	**0.0634**
Lighting, signage	E6	0.0412	0.0435
Mechanical and electrical facilities	E7	0.0474	**0.0584**

Bolded numbers in the table represent those that are impacted or have a high level of impact

(Baig et al. 2022; Šomodíková et al. 2016; Zhao et al. 2023; Thakkar et al. 2023). Therefore, during preventive maintenance, attention should be paid to the status of these two components. On the contrary, the C_K values of drainage systems and electromechanical facilities are lower, while the C_I values are higher, which means they are more likely to become fault source components. When these components fail, it may also affect other components. For example, poor drainage system and power outage of mechanical and electrical facilities can further accelerate the corrosion of steel structures. Therefore, in daily inspections, it is necessary to ensure that these two components remain in good working condition.

$$\left[C^T\right]' = \begin{pmatrix} 0 & 1/2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/2 \\ 1/5 & 0 & 1/5 & 1/5 & 0 & 1/5 & 0 & 0 & 0 & 0 & 0 & 0 & 1/5 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/7 & 0 & 1/7 & 0 & 0 & 1/7 & 0 & 1/7 & 1/7 & 0 & 0 & 0 & 1/7 & 1/7 \\ 1/8 & 1/8 & 0 & 0 & 0 & 1/8 & 1/8 & 1/8 & 1/8 & 0 & 0 & 1/8 & 1/8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/2 \\ 1/4 & 1/4 & 0 & 1/4 & 1/4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/3 & 0 & 0 & 0 & 1/3 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/3 & 0 & 0 & 1/3 & 0 & 0 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/6 & 1/6 & 1/6 & 0 & 1/6 & 1/6 & 1/6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1/3 & 1/3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1/3 & 0 & 0 \\ 0 & 0 & 1/5 & 1/5 & 0 & 1/5 & 0 & 0 & 0 & 0 & 1/5 & 0 & 1/5 & 0 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 1/4 & 0 & 1/4 & 0 & 0 & 0 & 0 & 0 & 1/4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \tag{8}$$

4.2.2 Bridge status rating

Based on the disease situation of the background bridge, the relevant components were evaluated according to the 'Standards for Technical Condition Evaluation of Highway Bridges' (hereinafter referred to as TCEB). Finally, the independent fault scores of each secondary indicator are obtained. Then, as described in Section 2, the data is substituted into Eq. (5) to obtain the bridge evaluation results based on the Pagerank algorithm, as shown in Table 2.

4.3 Comprehensive evaluation results

The evaluation results were compared using the TCEB and the methods proposed in this article in terms of first level indicators and overall scores, as well as various components of ancillary facilities, as shown in Fig. 6.

The comparison between the primary indicators and the overall evaluation results shows that there are significant differences in the scores of the cable-stayed system, main girder, and cable tower, while others are basically the same. This is mainly because the improved indicator system has added health monitoring indicators such as main girder deflection, cable force, and cable tower alignment. The influencing and the influenced degree on the main beam alignment and cable force are both significant, so the scoring

Table 2 Evaluation Results Considering Component Correlation

Primary indicators	Secondary indicators	Rating of secondary indicators	Evaluation level of secondary indicators	Rating of primary indicators	Overall rating value
Stay cable System	Visual inspection of stay cables	75.5	3	71.14	77.75 (Level 3)
	Cable forces	53.7	4		
Main girder	Visual inspection of main girder	40.1	4	51.71	
	Alignment of main girder	78.8	3		
Main tower	Visual inspection of main tower	77.8	3	85	
	Alignment of main tower	89.8	2		
Substructure	Pier	94.1	2	95.07	
	Foundation	99.1	1		
	Bearing	83.3	2		
	Riverbed	100	1		
Auxiliary facilities	Bridge deck pavement	84.0	2	88.55	
	Expansion joint	86.8	2		
	Longitudinal damping device	96.4	1		
	Railing and guardrail	84.8	2		
	Drainage system	92.3	2		
	Lighting, signage	97.8	1		
	Mechanical and electrical facilities	95.3	1		

values of monitoring indicators will affect the correlation between components, thereby affecting the final evaluation results.

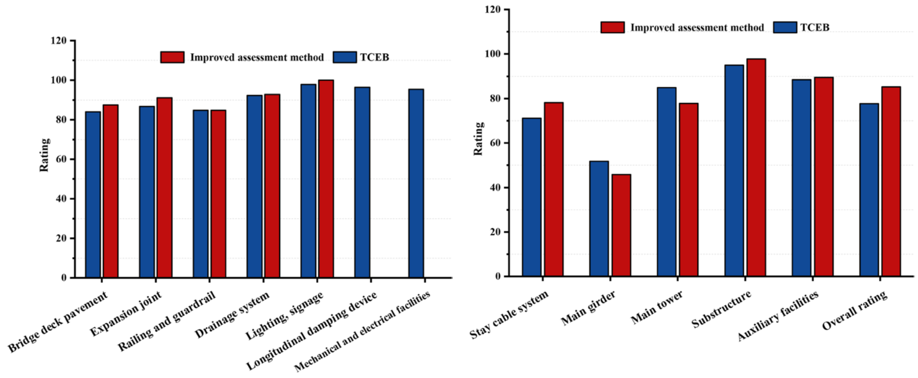
The final overall rating of the bridge in this article is 77.75, which is a Level 3 bridge. The rating in the TCEB is 85.3, which is a Level 2 bridge. The correlation between bridge components has an undeniable impact on the overall state of the bridge.

Compared to the TCEB, the auxiliary facilities have added longitudinal damping devices and electromechanical facilities, and the scores of each component are not significantly different. Among them, the bridge deck pavement, expansion joint devices, drainage systems, and lighting components will have a slight decrease in status scores due to the correlation of other components.

Compared to the TCEB, the method proposed in this article combines the impact of component failures and considers both health monitoring and manual inspection indicators, making the evaluation results more comprehensive and reliable, providing a reliable basis for the subsequent repair and maintenance of bridges.

5 Conclusions

This article takes cable-stayed bridges as the research object and proposes a new evaluation method based on component correlation. The following conclusions are drawn:



(a) Comparison of primary indicators and overall scoring results (b) Comparison of scoring results for ancillary facility components

Fig. 6 Comparison between the evaluation method in this article and the TCEB

(1) A comprehensive evaluation method for cable-stayed bridges considering component correlation has been proposed. A directed graph for the fault transmission of each component of the cable-stayed bridge is established, and the correlation of each component is analyzed based on the Pagerank algorithm. Finally, a cable-stayed bridge condition evaluation method that integrates the fault rate generated by each component separately and the fault rate generated by the fault correlation of other components.

(2) By solving the correlation between the components, it can be seen that the main girder alignment, cable force and main tower alignment are affected to a greater extent and influence range, in which the C_K value is greater than 0.068 and the C_I value is greater than 0.063, which indicates that the influence range of these three indexes is larger, and it is particularly important for the monitoring of the bridge's health condition; Visual inspection of main girder and the bearing C_K is larger than 0.069, the C_I is smaller than the smaller than 0.055, belonging to the failure appearance components, in preventive maintenance should focus on; drainage system and mechanical and electrical facilities on the contrary, C_K is less than 0.047, C_I is greater than 0.058, belonging to the failure source components should focus on in the daily inspection.

(3) Compared with the specifications, the method proposed in this article considers component correlation, making the evaluation results of the main components of cable-stayed bridges more reliable; Due to the correlation of components, the evaluation results of ancillary facilities have decreased. This provides reference for bridge maintenance decision-making.

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Authors' contributions
Xiaoling Liu: Conceptualization, Methodology, Writing–original draft. Ying Liu: Data analysis. Bing Wang: Data analysis.

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Availability of data and materials
Most data and models generated and used during the study appear in the published article. However, some information is proprietary or confidential in nature and may only be provided with restrictions.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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