Research on the Safety Evaluation of the Operation Performance of the Sluice Gate Based on Modified Fuzzy Comprehensive Evaluation Method

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Abstract. Traditional safety evaluation methods of the sluice gate based on expert knowledge have failed to comprehensively consider the weights and relationships between indicators. The fuzzy comprehensive evaluation method (FCEM) is an analytical approach using artificial intelligence (AI) technique, offering an effective solution to address the uncertainty, fuzziness, and fuzzy reasoning of gate indicators. This study introduces a safety evaluation method for the gate based on the improved FCEM. A systematic evaluation index system is proposed, which considers five key aspects: appearance quality, corrosion conditions, material performance, welding quality, and results of strength tests from on-site inspections. The safety levels of the sluice gates are categorized into five levels ranging from high to low. The weights of each evaluation indicator are determined using the modified Analytic Hierarchy Process (AHP). Subsequently, the FCEM is applied to assess the operational safety status of sluice gates. The analysis is performed using the fifth operational sluice gate at the Xin'anjiang Hydropower Station as a case study. The evaluation results demonstrate a high level of consistency for the gate, highlighting the method's notable accuracy and applicability. This study offers a crucial theoretical foundation and practical significance in ensuring the safe and stable operation of sluice gates.

Keywords: Sluice gates; Safety evaluation; Analytical Hierarchy Process; Fuzzy comprehensive evaluation method

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1 Introduction

Steel sluice gates are vital structures in the field of hydraulic engineering, serving as important mechanisms for water discharge and flow control. Their safe and reliable operation plays a crucial role in ensuring the overall safety of reservoir dams and flood control systems. Therefore, conducting safety assessments for the gates is imperative to promptly identify potential safety hazards within the gate's structure, laying a fundamental groundwork for classifying and reinforcing the safety of the sluice gates.

Research on the safety evaluation of the gate is a multidimensional and multifactorial subject [1, 2]. Currently, the widely used comprehensive evaluation method for gate safety assessment is based on knowledge engineering. This method incorporates on-site testing data and expert knowledge. The expert group, after conducting investigations, testing, and reviews, evaluates the results report according to specific evaluation standards. They then comprehensively analyze each project and link, and finally propose a conclusion for the safety appraisal. Although this method provides qualitative assessment results, it does not account for the interplay of influencing factors or their relative weights, thus lacking the ability to establish sluice gate grades quantitatively.

To address the limitations of traditional expert knowledge-based safety evaluation methods, various safety evaluation indicator systems and evaluation models have been proposed and developed, achieving significant success in engineering applications [3-5]. The Analytic Hierarchy Process (AHP), a technique combining both subjective and objective weighting methods, finds extensive application in weights calculation for indicator systems in multi-dimensional target decision statistics, thereby facilitating a hierarchical and systematic approach to resolving intricate problems [6-8]. C. Zhang et al [9] introduced a fuzzy post-mining method based on the AHP, contrasting it with four conventional methods and demonstrating its exceptional performance in extracting associative rules. However, this traditional AHP uses a 1-9 scale, which is too detailed and can potentially lead to significant errors. The modified AHP employs three scales to indicate the level of importance between factors, which significantly reduces the iteration number and improves the calculation accuracy. This modified AHP has been employed in gate safety assessment field and displays good application effects [10].

Fuzzy evaluation theory is a technique within the domain of artificial intelligence (AI) used for tackling issues involving uncertainty and vagueness. It contributes to enhancing the adaptability and decision-making capability of AI systems. By combination of the AHP and fuzzy mathematics theory, the FCEM introduces the notion of a fuzzy complementary matrix and employs ranking fuzzy sets to evaluate the significance of safety warning indicators. The FCEM utilizes a comprehensive assessment approach, transparent calculation procedures, and more precise assessment outcomes, making it widely applicable in engineering scenarios. J. Hu et al. [11] quantitatively assessed the seismic hazards of a 3080.25 km^2 region using the FCEM method. The assessment outcomes exhibit a certain level of objectivity and precision. C. Zhong et al. [12] employed the AHP and entropy technique to construct a water quality evaluation system, and established a health risk assessment model based on triangular fuzzy theory. X. Wu and F. Hu [13] formulated a holistic evaluation framework for ecological carrying capacity. D. C. Ratnayake et al. [14] employed the multi-impact factor technique utilizing ArcGIS and the AHP to ascertain the optimal locations for soil moisture monitoring. The application of FCEM provide a scientific method for evaluating the operational performance in these fields. There are also some attempts to utilize the FCEM method with traditional AHP for the safety evaluation of the sluice gates [15]. However, there exist a wide range of gate structures and diverse operating environments, yet the safety evaluation method for gate operation requires further enhancement.

In response to the requirement of research on safety evaluation in the field of gate engineering, the improved FCEM is introduced in current research by integrating traditional safety assessment methodology with the fuzzy mathematical theory sourced from the domain of AI. A safety evaluation index system is developed for the safe operation of sluice gates, using a modified three-scale AHP to ascertain the weights of evaluation indicators. Furthermore, thresholds and evaluation standards for gate safety evaluation indicators are established based on on-site inspection data, national regulations, and expert knowledge systems. The safety level of the gate's operation status is determined using FCEM. To illustrate the application of the proposed method, the fifth intake working gate of Xin'anjiang Hydropower Station is used as a case study. This research study aims to provide a scientific basis for the safe operation and maintenance management of the sluice gates.

2 Procedure of the Modified Fuzzy Comprehensive Evaluation Method

2.1 Establishment of a Safety Evaluation Index System for Gate

A comprehensive performance evaluation index system is established for gate operations, as depicted in Fig. 1. This evaluation system is structured into three layers: the target layer, criterion layer, and indicator layer. The target layer emphasizes the comprehensive safety evaluation of gate operations, with the criterion level encompassing criteria such as appearance quality (u_1), corrosion condition (u_2), material performance (u_3), welding quality (u_4), and stress condition (u_5).

Several indicators are selected in indicator layer. Two indicators, namely component damage u_{11} and water stop condition u_{12}, are selected in u_1. Five indices, namely panel corrosion u_{21}, main beam corrosion u_{22}, longitudinal beam corrosion u_{23}, small crossbeam corrosion u_{24}, and overall average corrosion u_{25}, are selected in u_2. Two indicators, namely chemical composition u_{31} and tensile strength u_{32}, are selected in u_3. Crack u_{41} and incomplete penetration u_{42} are selected as indicators in u_4. Five strength indicators, namely converted stress of the panel u_{51}, normal stress of the main beam u_{52}, shear stress of the main beam u_{53}, converted stress of the main beam u_{54}, and normal stress of the longitudinal beam u_{55}, are selected in u_5.

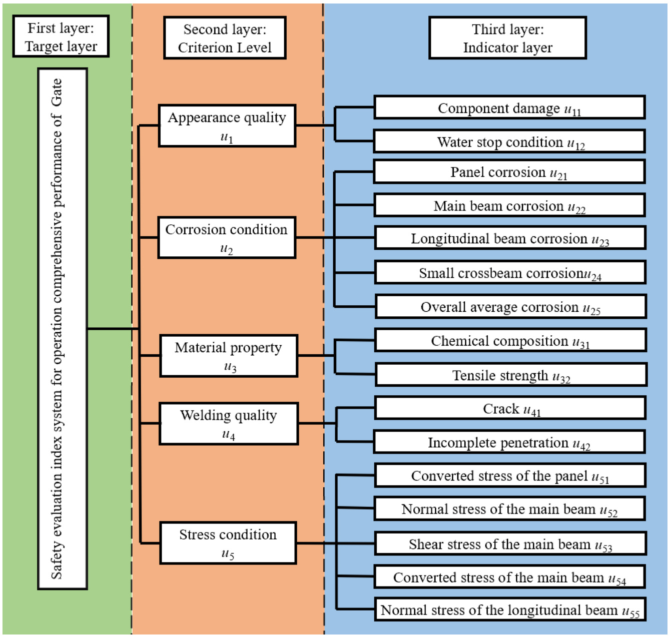


Fig. 1. Evaluation index system for the gate's operation performance

2.2 Definition of the Safety Evaluation Standards for Gates

The comprehensive safety performance evaluation and classification of gates are categorized into five levels: E = {Level I, Level II, Level III, Level IV, Level V}. Level I ~ V signifies generally undamaged, a certain degree of damage, a deteriorating trend, significant damage, complete destruction of the gate, respectively. The corresponding intervals for the five safety levels are as follows: V_{I}=[0.8, 1.0), V_{II}= (0.6, 0.8], V_{III}=(0.4, 0.6], V_{IV}=(0.2, 0.4], V_{V}=(0, 0.2].

2.3 Determine the Weight of Indicators Based on the Modified AHP

The modified three-scale AHP employs a scale of 0-2 to indicate the level of importance between factors. To quantify the results, we will represent them using numerical values denoted as c_{ij}.

$$c_{ij} = \begin{cases} 0 & i \text{ is less important than } j \\ 1 & i \text{ is the same important as } j \\ 2 & i \text{ is more important than } j \end{cases} \tag{1}$$

Judgment matrix $A=(a_{ij})$ is constructed as follows.

$$a_{ij} = \begin{cases} r_i - r_j & r_i > r_j \\ 1 & r_i = r_j \\ (r_i - r_j)^{-1} & r_i < r_j \end{cases} \tag{2}$$

r_i and r_j are the sum of rows of the judgment matrix, $r_i = \sum_{k=1}^{n} c_{ik}$, $r_j = \sum_{k=1}^{n} c_{jk}$, $i, j =$ 1, 2, …, n.

The indicator weight signifies the level of influence that the indicator has on the evaluation object. The weight set $W = \{w_1, w_2, \ldots, w_n\}$ were obtained for the evaluation indices using the improved three-scale AHP. The weights of the indicators in the subordinate criteria layer, denoted as u_i, are defined as w_i (i=1, 2, 3, 4, 5, 6) in the target layer.

$$w_i = \frac{M_i^{\frac{1}{n}}}{\sum_{i=1}^{n} M_i^{\frac{1}{n}}}, \quad M_i = \prod_{n}^{j=1} a_{ij} \tag{3}$$

M_i is the product of the elements in each row of the judgment matrix.

2.4 Definition of the Evaluation Matrix

The concept of FCEM aims to utilize the theories of membership degree to facilitate the transformation in the evaluation process from qualitative to quantitative to qualitative. By defining the evaluation index set as $Y=\{y_1, y_2, \ldots, y_m\}$, and the evaluation grade set as $E=\{e_1, e_2, \ldots, e_p\}$, the membership matrix R can be defined as follows.

$$\boldsymbol{R} = \left(r_{gh}\right)_{m\times p} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1p} \\ r_{21} & r_{22} & \cdots & r_{2p} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mp} \end{bmatrix} \tag{4}$$

Among them, m is the number of evaluation indicators, p is the number of evaluation levels, and r_{gh} represents the membership degree of the g^{th} evaluation indicator y_g belonging to the h^{th} evaluation level e_h.

The corrosion rate, stress, and deformation in the safety evaluation model are all negative indicators, meaning that the smaller the indicator value, the safer the system. Membership function for level I ~ V is employed to denote the membership degree of the indicator.

2.5 Calculation of the Comprehensive Membership Degree

By multiplying the evaluation matrix R_i, which consists of single factors, with the weight vector W_i, the evaluation vector $B_i = W_{ij} \times R_{ij}$ is obtained for each primary indicator. These evaluation vectors, along with the factors R_{ij}, are used to form the first-level fuzzy comprehensive evaluation matrix B. The first-level indicator weight value W_i, obtained through the improved AHP method, is then combined with the fuzzy overall evaluation matrix B. Thus, the comprehensive performance of gate operation can be assessed using the fuzzy comprehensive evaluation model.

$$D = \boldsymbol{W}_i \circ \boldsymbol{B} \tag{5}$$

The formula incorporates D as the comprehensive membership degree of FCEM, W_i as the weight vector of the criterion layer, and $\circ$ as a fuzzy operator. The weighted average type of fuzzy operator, which prioritizes multiplication before summing, is widely employed due to its inherent stability and effective utilization of information.

3 Case Study

3.1 Project Overview

The Xin'anjiang Hydroelectric Power Station, located in Jiande City, China, primarily generates electricity and also provides comprehensive social benefits such as flood control, irrigation and climate regulation during high tides. In order to ensure the safe and reliable operation of the power plant and monitor the operation of the water inlet gate, this paper proposes an improved fuzzy analytic hierarchy process for the safety testing and assessment of the fifth gate.

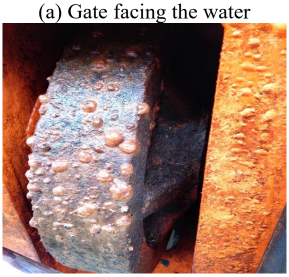
3.2 Analysis of On-Site Test Results of the Gate

Appearance Inspection Results.

As shown in Fig. 2, the overall condition of the sluice gate was good, with no damage or deformation of the components found. The components of the water sealing device were complete and securely connected. However, Fig. 2 (c) depicts numerous rust marks on the surface of the main wheel of the sluice gate that require removal. Some shallow rust pits can be seen, with maximum depths of approximately 0.3 millimeters. Fig. 2 (d) shows deposits on a local area of the sluice gate, but they have not caused any damage to the gate's paint layer.

(a) Gate facing the water

(b) Gate backwater surface



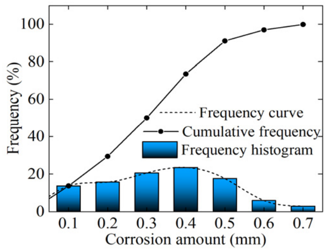
(c) Main wheel surface

(d) Attachments on the gate.

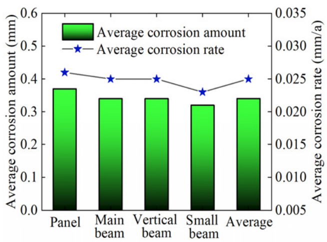
Fig. 2. Appearance inspection diagram of the sluice gate

Corrosion Test Results.

The frequency distribution histogram illustrating the corrosion amount of the gate can be obtained, as depicted in Fig. 3 (a). The average corrosion amount and the corrosion rate of each major component of the gate are listed in Fig. 3 (b). According to the statistical chart of the frequency distribution of the corrosion amount, it can be seen that the corrosion amount of the sluice gate was mainly between 0.1 mm and 0.5 mm, with a frequency of 91.2%. The average corrosion amounts of the panel, main beam, vertical beam, and small beam were 0.37 mm, 0.34 mm, 0.34 mm, and 0.32 mm, respectively. The average corrosion rate ranged from 0.023 mm/year to 0.026 mm/year.



(a) Frequency distribution

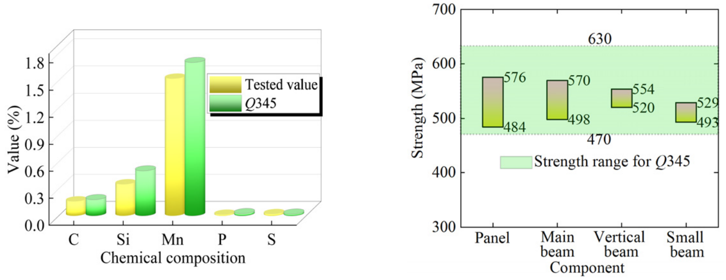


(b) Corrosion amount and rate

Fig. 3. Corrosion statistics of main components of the gate

Material Property Test Results.

Rear flange of the edge beam of the sluice gate was selected for sampling purposes. The test results of chemical composition and tensile strength for the main component are reported in Fig. 4. The data indicate a congruence between the chemical composition of the gate specimen and that of low-alloy structural steel *Q*345. Additionally, the tensile strength of the principal gate components aligns with that of *Q*345. It is evident that the material used for the main components of the gate is low-alloy structural steel *Q*345.



(a) Chemical composition test results (b) Tensile strength test results

Fig. 4. Material property test results of the main components of the gate

Welding Quality Results.

The results of the ultrasonic weld testing show no crack defects were detected in the examined welds of the gate. One inclusion defect was found in the weld connecting the main web plate and the rear flange plate of beam $6^{\#}$. No defects requiring recording were identified in the welds of the side beam of the sluice gate. No defects requiring recording were found in the welds connecting the lifting lug plate of the gate. The defects identified during the inspection are allowable and don't affect the safe operation of the gate and don't require any treatment.

Strength Test Results.

The detection conditions of the gate include an upstream water level of 100.08 m, no downstream water, a bottom sill elevation of 70.40 m, and an acting water head of 29.68 m. The results of the detection are presented in Table I. The maximum normal stress on the measuring point of the main crossbeam and the longitudinal beam is 63.0 MPa and 12.2 MPa, respectively, which is below the permissible value of 213.8 MPa. Additionally, the maximum converted stress at the measuring point of the main beam web is 68.7 MPa, which is below the allowable value of 235.18 MPa. The maximum shear stress is 37.7 MPa, also remaining below the allowable value. Furthermore, the converted stress at the measuring point of the gate panel is 47.0 MPa, below the allowable value of 352.77 MPa. Based on the test results, it can be concluded that the stress at each measuring point of the gate falls within the allowable range, demonstrating the fulfilment of design requirements.

Table 1. The measured value of the measure point at the gate

Measuring points	Main beam's normal stress							
	1	2	3	4	5	6	7	8
Stress (MPa)	37.1	44.1	49.2	57.5	59.7	54.0	54.6	**63.0**
Measuring points	Main beam's shear stress		Main beam's converted stress		Longitudinal beam's normal stress		Panel's converted Stress	
	10	11	10	11	9			
Stress (MPa)	35.1	**37.7**	64.2	**68.7**	**12.2**		**47.0**	

Safety Level Assessment of the Gate Based on FCEM.

A comparison matrix C is constructed for the indicator layer using Eq. (1). The weights of the criterion layer and the indicator layer are calculated based on expert judgment, following the same process, and presented in Fig. 5. The weights w_i of the criterion layer u_i and the weights w_{ik} of the indicator layer u_{ij} to the criterion layer u_i are calculated using Eq. (3). The weight results indicate that for the secondary index corrosion condition u_2, the two indicators, panel corrosion u_{21} and main beam corrosion u_{22}, are of greater significance. In the strength condition u_5, the converted stress (u_{53}) and shear stress (u_{52}) in the main beam hold higher importance. Welding quality (u_4) and strength condition (u_5) stand out as particularly significant for the primary indicators.

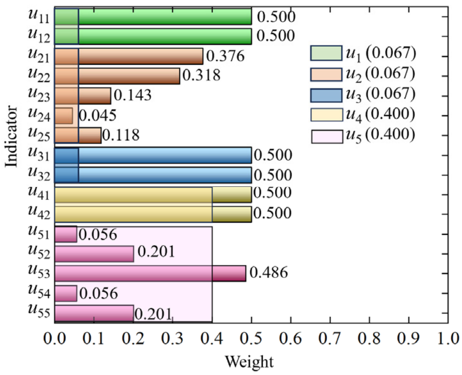


Fig. 5. The weights of the criterion layer and the indicator layer

The qualitative factors, which include component damage (u_{11}), water resistance (u_{12}), tensile strength (u_{31}), chemical composition (u_{32}), cracks (u_{41}), and incomplete welding (u_{42}), are evaluated for their membership degrees using the expert scoring method. The remaining variables are standardized based on a threshold. The membership degree matrix is derived and presented in Table II. Considering the results of field tests, with an evaluation index *m* of 16 and an evaluation level *p* of 5 in Eq. (4), the fuzzy evaluation set *R* is determined.

Table 2. Data sheet of the calculation process

Index	Measured data	Threshold	Membership matrix
u_{11}	Good	Qualitative	[0.90, 0.10, 0, 0, 0]
u_{12}	Good	Qualitative	[1, 0, 0, 0, 0]
u_{21}(mm/a)	0.026	0.200	[0.69, 0.31, 0, 0, 0]
u_{22}(mm/a)	0.025	0.200	[0.72, 0.28, 0, 0, 0]
u_{23}(mm/a)	0.025	0.200	[0.72, 0.28, 0, 0, 0]
u_{24}(mm/a)	0.023	0.200	[0.78, 0.22, 0, 0, 0]
u_{25}(mm/a)	0.025	0.200	[0.72, 0.28, 0, 0, 0]
u_{31}	Consistent	Qualitative	[1, 0, 0, 0, 0]
u_{32}	Qualified	Qualitative	[1, 0, 0, 0, 0]
u_{41}	Qualified	Qualitative	[1, 0, 0, 0, 0]
u_{42}	Qualified	Qualitative	[1, 0, 0, 0, 0]
u_{51}(MPa)	63.0	213.80	[0.10, 0.90, 0, 0, 0]
u_{52}(MPa)	37.70	128.30	[0.03, 0.97, 0, 0, 0]
u_{53}(MPa)	68.70	235.18	[0.04, 0.96, 0, 0, 0]
u_{54}(MPa)	12.20	213.80	[1, 0, 0, 0, 0]
u_{55}(MPa)	47.00	352.80	[0.83, 0.17, 0, 0, 0]

The weighted average fuzzy operator is utilized to calculate the comprehensive membership degree *D* using Eq. (5). The evaluation follows the principle of maximum membership degree. Table III displays the results of the fuzzy comprehensive evaluation for the operational safety assessment model of the gate.

Following the principle of maximum membership degree, the gate attains the highest membership degree in level I, surpassing 50%. Therefore, the gate is classified as being in level I state, ensuring safe and stable operation. In the practical engineering, the safety evaluation result of the fifth water inlet working gate is rated as safe, with no safety hazards affecting the operation of the gate found. The evaluation results demonstrate a high level of consistency for the gate, highlighting the method's notable accuracy and applicability.

Table 3. Evaluation results of the performance of the gate

Level	I	II	III	IV	V	Result
Membership degree	0.68	0.32	0	0	0	Level I

4 Conclusion

1) A comprehensive performance and safety evaluation index system for gates was established based on FCEM. This system comprises five primary indicators and sixteen secondary indicators. The weight of each indicator was determined by combining

the judgment matrix and the modified AHP. The evaluation level and threshold of the indicators were set based on the principles of fuzzy mathematics and membership theory. A set of fuzzy evaluation indicators was established using measured data from the gates. The weighted average fuzzy operator was employed to calculate the comprehensive membership degree, thus evaluating the safety level of gate operation based on the maximum membership principle.

2) The proposed method's effectiveness was verified through practical engineering applications in Xin'anjiang hydropower station. The fuzzy evaluation process, based on the modified AHP method, reveals that panel and main beam corrosion have greater importance in assessing corrosion conditions. Additionally, the main beam's converted stress and shear stress are of greater significance in evaluating strength conditions. For the primary indicators, welding quality and strength conditions hold particular importance, exerting a substantial impact on the gate's safe operation. The safety evaluation results, based on the FCEM, indicate that the gate is in a level I state, ensuring safe and stable operation, and meeting the gate's design requirements.

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