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Operation safety evaluation system of ship lock based on extension evaluation and combination weighting method

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ABSTRACT

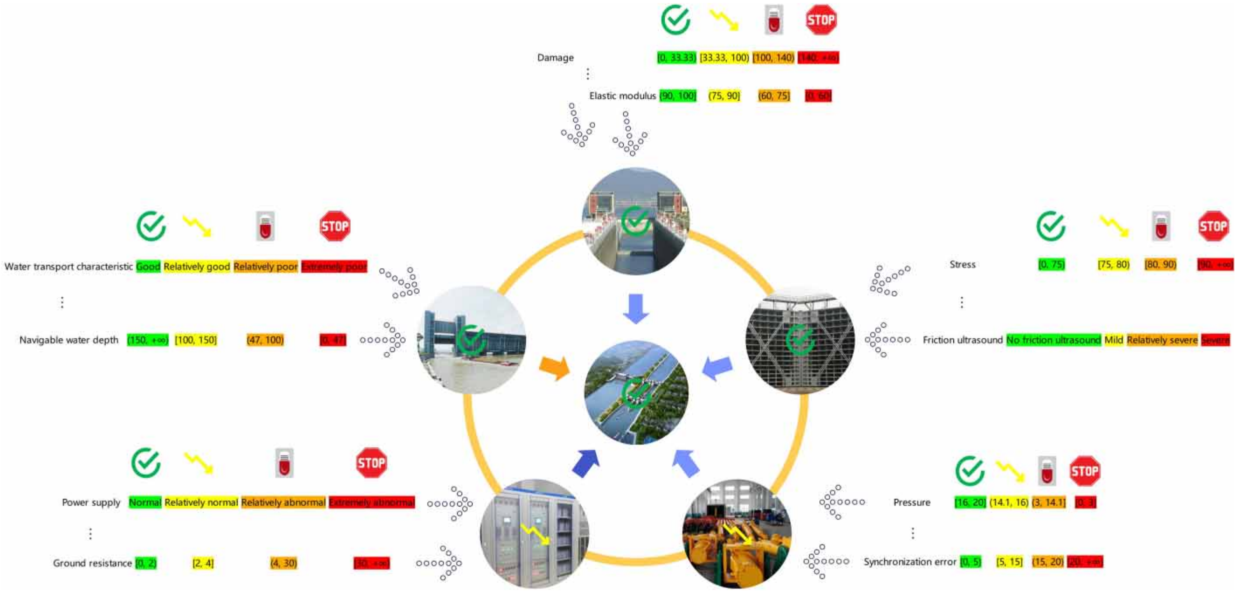
Ship locks are the most widely used, promising, and important type of navigation structure in the world at present. It is, therefore, crucial to evaluate the operation safety of a ship lock in service. However, the determination of indicator thresholds is challenging. Accordingly, this paper describes the systematic study of the evaluation system of ship lock operation safety. First, the safety accidents of ship locks are counted. According to the rhombic thinking mode (that is, the thinking mode of 'first divergence and then convergence'), with the help of extenics, a multi-indicator hierarchical indicator system including 5 first-class indicators and 47 second-class indicators for the safety evaluation of ship lock operation is established, and 4 safety evaluation grades are classified: normal, deterioration, early warning, and shutdown. The threshold range of each indicator at each grade is determined individually. Second, based on the idea of multi-factor optimization and integration, the process and the matter-element model of ship lock operation safety evaluation based on extension theory are proposed. Then the weight of the safety indicator is determined by the combination weighting method. The evaluation result is consistent with the actual situation.

Key words: extension evaluation model, indicator system, operation safety, ship lock

HIGHLIGHTS

- The safety accident examples of ship locks are counted.
- The multi-level and multi-index system and standard for comprehensive evaluation of ship lock operation safety are constructed.
- The evaluation method and process of ship lock operation safety based on extension theory are proposed.
- Game theory combines the weights of the analytic hierarchy process and the coefficient of variation method.

GRAPHICAL ABSTRACT



1. INTRODUCTION

A ship lock is a kind of navigable building that enables a ship to overcome the concentration drop of the water level of a channel, and is primarily composed of an approach channel, the head of the gate, a lock chamber, and a water conveyance system, i.e., an open complex giant system (Zhang 2001; Yao 2003). As an important node project on a waterway, once a lock fails to operate normally, it will lead to the blockage of the entire channel, the interruption of navigation (Changjiang 2004), and potentially disastrous consequences. Therefore, ship lock operation safety plays a decisive role in shipping safety in an inland waterway.

China was the earliest country in the world to build a navigable building of artificial canals for shipping with 1,041 ship locks under construction and having been built. Thousands of ship locks have been applied in the inland shipping hubs of Belgium and the Netherlands (Li *et al.* 1999), but there are various types of damage that affect the operation safety of a ship lock (Chen 2012). In recent years, accidents that have caused serious consequences due to ship lock failure have also become common around the world. Many ship locks have had major safety problems in operation, such as the collapse of the lock wall, the water leakage of the foundation, the tearing of the working gate panel, and the fracture of the top pivot pull rod, as listed in Table 1 (Chen 1983; Jin 1983; Lin 2008). Due to the suspension of activity caused by ship lock breakdown and repair, ships were delayed for 1 day every 52 days in transit on average, resulting in extra hundreds of millions of dollars spent per year by businesses and consumers. In summary, it is imperative to evaluate the operation safety status of ship locks.

2. LITERATURE REVIEW

Because the safety evaluation of a lock has been insufficiently researched, the findings are limited. This section introduces the research results achieved so far around the world in the professional field of ship lock operation safety evaluation.

In terms of the evaluation method, Zhang (2013) adopted a safety assessment method based on the reliability theory. This method was highly dependent on data. The weighting method used in this research is also single.

In terms of the evaluation basis, the Ministry of Transport of China issued ‘Technical Code of Maintenance for Navigation Structure’ (JTS 2018) in 2018. The technical status grade standards of ship lock equipment and facilities were proposed. This was followed in 2019 by ‘Technical Specification for Safety Detection and Assessment of Navigation Junction’ (JTS 2019), which involves specific requirements related to ship lock safety assessment. However, there is a lack of hydraulic power standards.

In terms of the evaluation content, the ‘Technical Code of Maintenance for Navigation Structure’ puts forward the evaluation content of the detection result of navigational water flow conditions, hydraulic characteristics of a water transmission

Table 1 | Statistics of ship lock accident cases

Serial No.	Time	Ship lock	Region	River (or water system)	Accident overview	Consequence
1	8 March 1982	Gezhouba Ship Lock No. 2	Yichang, Hubei, China	Yangtze	The pull rod A at the top pivot of the left miter gate of the lower gate head suddenly broke into two segments, causing the left door to tilt	The shipping across the dam of the Yangtze River was immediately completely interrupted for 9 days
2	16 January 2007	Huai'an Ship Lock	Huai'an, Jiangsu, China	Beijing–Hangzhou Canal	The panel near the diagonal column at the right bottom of the miter gate (the door panel closest to the gradient section) was severely damaged, tearing a hole with a size of about 1 m^2, and only a few parts of the gate panel between the beam lattices were connected to the gate	The safety of ship lock operation was endangered
3	June 2012	Mengcheng Ship Lock	Mengcheng, Anhui, China	The main stream of the Guo River, a tributary of the Huai River	Emergency repair of broken navigation	15 days
4	13 January 2013	Fuyang Ship Lock	Fuyang, Anhui, China	Shaying River	The top hub of the downstream gate suddenly failed	The ship lock was suspended for emergency repair, it was forced to interrupt navigation operations for 20 consecutive days, and about 200 ships downstream and nearly 100 ships upstream were stranded
5	18 May 2014	Weishan second-line Ship Lock	Weishan, Shandong, China	The main channel of the Beijing–Hangzhou Canal	The copper cap of the bottom pivot of the bottom running part of the upstream left-bank underwater gate was seriously worn, and the gate sank, hindering the normal operation of the gate, resulting in the abnormal noise failure of vibration of the upstream left-bank gate	15 days taken for broken navigation and emergency repair
6	4 January 2015	Gezhouba Ship Lock 3	Yichang, Hubei, China	Yangtze	A horizontal penetrating crack appeared at the bottom of the lower right herringbone gate	The loss of water stopped functionality, and serious water leakage occurred
7	18 February 2020	Shihutang Ship Lock	Taihe, Jiangxi, China	Ganjiang	About 80 m in the middle of the wall of the waterfront lock chamber collapsed outward	Broken navigation
8	15 December 2022	Miraflores Ship Lock	Panama City, Panama	Panama Canal	A fire broke out in a mechanical tunnel	Ship traffic was temporarily suspended and a tanker was stranded for several hours

system, gate, and valve. Kolosov (2002) established an accident risk assessment model of a gate and a lock wall. Xu (2007) carried out the safety analysis of a gate structure. These studies considered hydraulic and metal structures but did not consider hydraulic, electrical systems, or hydraulic power.

In terms of the evaluation indicator, Senitskiy & Kuzmin (2012) studied the dynamic characteristics of a ship lock. The precise design relationship formula between the inherent vibration and forced vibration of the gate bottom is proposed. Zhang (2013) conducted a qualitative and quantitative safety assessment, which made the result more scientific and credible.

These research results have played an important role in promoting the safety evaluation of ship lock operation, but due to many factors affecting the safety of ship lock operation and the work to be done, there is no relevant and complete safety evaluation system around the world (Teng 2011).

3. ESTABLISHMENT OF THE SAFETY EVALUATION SYSTEM

3.1. Extension evaluation method

Evaluation methods are generally divided into subjective methods and objective methods, among the subjective methods, the fuzzy comprehensive evaluation method is commonly used. The extension evaluation method of the objective methods is adopted in this study, which can make use of the measured data of a ship lock and make the evaluation results more credible.

The extension evaluation method is a method that takes the indicator and characteristic value as matter-element and obtains the classic domain, the node domain, and the correlation degree using the evaluation standard (Shen 2007; Sun *et al.* 2007; Zeng 2014). In this study, according to the characteristics of ship locks and based on the system concept based on the overall situation, the extensibility theory (Yang & Cai 2000; Hu 2001; Jia *et al.* 2003; Zhang *et al.* 2013) is introduced to establish an extension evaluation model (Nabipour *et al.* 2020) for the safety of ship lock operation.

By studying the integrity of a ship lock and the extensibility of the evaluation matter-element, from the perspective of the matter-element analysis, each evaluation factor related to the operation safety of a ship lock is expressed by an information matter-element, and multiple evaluation factors form an information matter-element system (ship lock operation safety evaluation indicator system) according to a certain structure. The method of processing information is abstracted as matter-element transformation (Su *et al.* 2005), and the degree of the certain characteristic of the evaluation factor is reflected by the correlation function to realize the integrated evaluation of operation safety of a ship lock from qualitative to quantitative. The steps are as follows:

1. Classic and node domain

The classic domain is the threshold interval of the indicator for a certain grade, and the node domain is its interval for all grades:

$$R = \begin{bmatrix} N_j & \mathrm{N}_1 & \mathrm{N}_2 & \cdots & \mathrm{N}_\mathrm{m} \\ C_i & V_{i1} & V_{i2} & \cdots & V_{im} \end{bmatrix} = \begin{bmatrix} N_j & N_1 & N_2 & \cdots & N_m \\ C_1 & <a_{11}, b_{11}> & <a_{12}, b_{12}> & \cdots & <a_{1m}, b_{1m}> \\ C_2 & <a_{21}, b_{21}> & <a_{22}, b_{22}> & \cdots & <a_{2m}, b_{2m}> \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & <a_{n1}, b_{n1}> & <a_{n2}, b_{n2}> & \cdots & <a_{nm}, b_{nm}> \end{bmatrix} \tag{1}$$

where R is the classic domain matter-element of C_i about N_j, N_j is the jth safety grade divided ($j = 1, 2, \ldots$, m), C_i is the ith indicator ($i = 1, 2, \ldots$, m), and $V_{ij} = <a_{ij}, b_{ij}>$ is the magnitude range of C_i on N_j, i.e., the classic domain:

$$R_N = [N \quad C_i \quad V_i] = \begin{bmatrix} N & C_1 & <a_1, b_1> \\ & C_2 & <a_2, b_2> \\ & \vdots & \vdots \\ & C_n & <a_n, b_n> \end{bmatrix} \tag{2}$$

where R_N is the node domain matter-element of C_i about N, N is all grades, and $V_i = <a_i, b_i>$ is the magnitude range of C_i for N, that is, the node domain.

2. Matter-element to be evaluated

The actual status of the evaluation indicator is expressed as

$$R_P = [P \quad C_i \quad v_i] = \begin{bmatrix} P & C_1 & v_1 \\ & C_2 & v_2 \\ & \vdots & \vdots \\ & C_n & v_n \end{bmatrix} \tag{3}$$

wherein R_P is the matter-element to be evaluated of the evaluation object P, P is the evaluation object in the criterion layer of the ship lock operation safety evaluation indicator system, and v_i is the value of indicator C_i.

3. Single indicator correlation degree

$$K_{ij} = \begin{cases} -\dfrac{\rho(v_i, V_{ij})}{|V_{ij}|} & v_i \in V_{ij} \\ \dfrac{\rho(v_i, V_{ij})}{\rho(v_i, V_i) - \rho(v_i, V_{ij})} & v_i \notin V_{ij} \end{cases} \tag{4}$$

$$\rho(v_i, V_i) = \rho(v_i, \langle a_i, b_i \rangle) = \left| v_i - \frac{a_i + b_i}{2} \right| - \frac{b_i - a_i}{2} \tag{5}$$

$$\rho(v_i, V_{ij}) = \rho\big(v_i, \langle a_{ij}, b_{ij} \rangle\big) = \left| v_i - \frac{a_{ij} + b_{ij}}{2} \right| - \frac{b_{ij} - a_{ij}}{2} \tag{6}$$

where K_{ij} is the correlation degree of the ith evaluation indicator of the evaluation object P for grade j, $\rho(v_i, V_i)$ is the distance between point v_i and interval V_i, and $\rho(v_i, V_{ij})$ is the distance between point v_i and interval V_{ij} (Li & Wang 2020; Zhang & Wang 2020).

4. Multi-indicator comprehensive correlation degree

The weight of the evaluation indicator combined with its correlation degree is

$$K_j(P) = \sum_{i=1}^{n} W_i K_{ij} \tag{7}$$

where $K_j(P)$ is the comprehensive correlation degree of the evaluation object P about grade j, W_i is the weight of the ith indicator of the evaluation object, which satisfies $\sum_{i=1}^{n} W_i = 1$.

Then a target layer evaluation is conducted:

$$K_j = \sum_{i=1}^{n} W_i' K_j(P_i) \tag{8}$$

where K_j is the comprehensive correlation degree of the evaluation target about grade j and $K_j\ (P_i)$ is the comprehensive correlation degree of the ith evaluation object P_i about grade j.

5. Rating

The grade with the greatest correlation degree is the evaluation result.

$$K_{j'} = \max K_j \tag{9}$$

Then the evaluation target belongs to grade j'.

6. Evaluation process

The process of realizing the safety evaluation of ship lock operation is shown in Figure 1 (Sharafati *et al.* 2021).

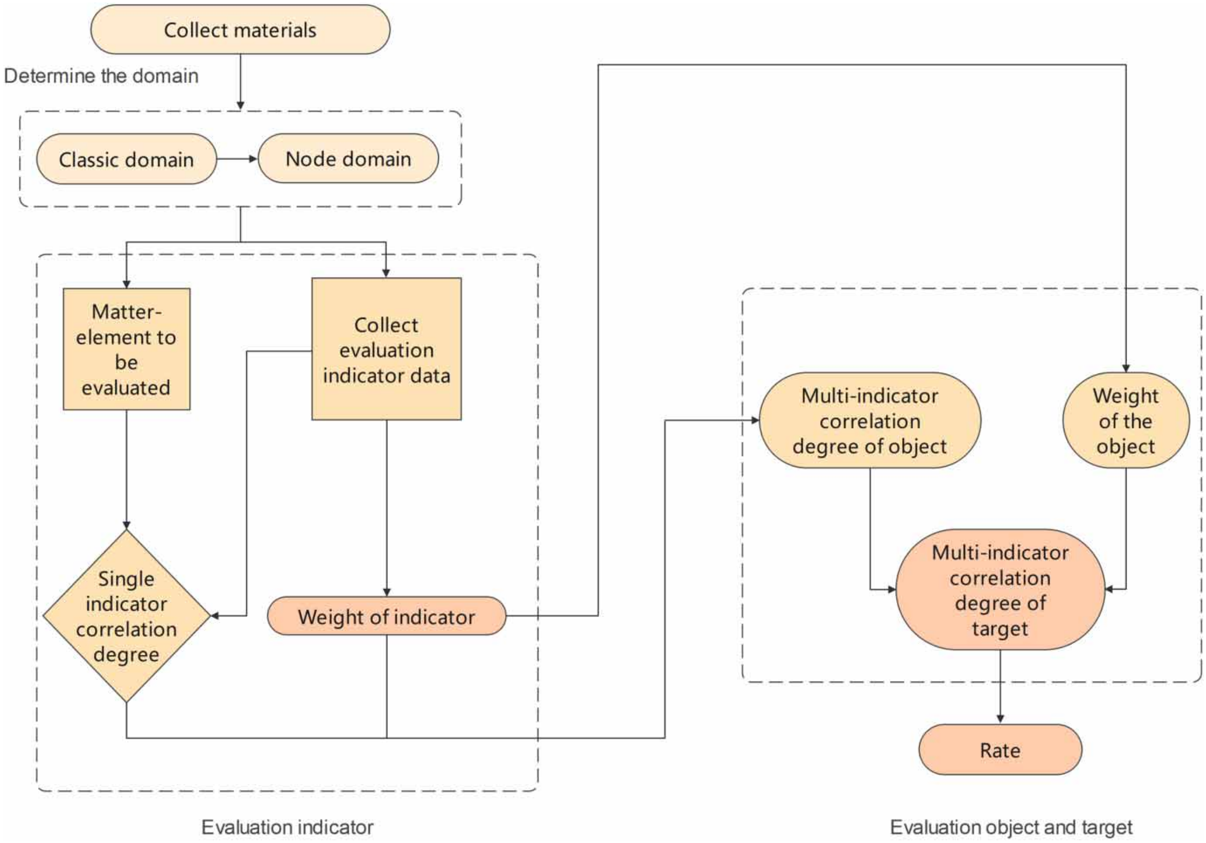


Figure 1 | Extension evaluation process.

3.2. Combination weighting method

The weight of the indicator represents the relative importance of each indicator to the evaluation. The weight can be subjectively determined based on expert opinions in combination with the special geographical and climatic conditions and structural characteristics of a ship lock. This method is easy to apply and professional advice can be obtained, but it is subjective and arbitrary (Wang *et al.* 2013). Instead, the objective weighting method aims to determine weight based on actual data and a processing algorithm, without relying on subjective judgments, but it lacks consideration of expert experience. In this study, a combination weighting method that both reduces information loss and appropriately reflects the importance of each indicator is used (Guo & Liu 2011; Li *et al.* 2020a). In this way, the weights that are obtained are more reasonable and the evaluation results are more reliable.

A combination weighting method (Li *et al.* 2019) usually has two ways to synthesize weights: the multiplication normalization method and the linear weighting method. The former has a ‘multiplier effect’–the bigger value is bigger and the smaller value is smaller, making the weights polarized. The latter has no weighted parameter standard and is highly subjective. A more reasonable weight value and more credible evaluation results can be obtained by determining the linear weighting parameters (Baghban *et al.* 2019) with game theory and then calculating the weight with the combination weighting method.

In this study, the objective extension evaluation method combined with game theory and the combination weighting method is used to evaluate the operation safety of a lock; this causes less artificial randomness than the subjective evaluation method combined with the combination weighting method in reference (Li *et al.* 2019).

3.2.1. Game theory combination weighting method

The game theory combination weighting method (Fan & Han 2006) maximizes advantages, reduces one-sidedness, and improves scientificity. The basic idea is to find compromises and minimize the deviation sum from basic weights (Lai *et al.* 2015; Zhang *et al.* 2021).

1. Construction of a possible weight set

The indicators are weighted with H methods to obtain the weight vector $\boldsymbol{W_h} = (W_{h1}, W_{h2}, \cdots, W_{hn})$. The arbitrary linear combination of these weight vectors is:

$$\boldsymbol{W} = \sum_{h=1}^{H} \alpha_h \boldsymbol{W_h} \, (\alpha_h > 0) \tag{10}$$

where α_h is the weight coefficient (Jeon & Paek 2021) and $\boldsymbol{W}$ is the possible weight vector of the basic weight sets.

2. Determination of the most satisfactory weight vector $\boldsymbol{W^*}$

The game assembly model (Xing 2016) is used to optimize α_h and minimize the difference between $\boldsymbol{W^*}$ and $\boldsymbol{W_h}$ (Li *et al.* 2020b) to find the most satisfactory weight vector $\boldsymbol{W^*}$:

$$\min \left\| \sum_{h=1}^{H} \alpha_h \boldsymbol{W_h} - \boldsymbol{W_{h'}} \right\|_2 \tag{11}$$

The best first derivative condition of the above formula is:

$$\sum_{h=1}^{H} \alpha_h \boldsymbol{W_h} \boldsymbol{W_{h'}^T} = \boldsymbol{W_{h'}} \boldsymbol{W_{h'}^T} \tag{12}$$

The corresponding linear formula is:

$$\begin{bmatrix} \boldsymbol{W}_1\boldsymbol{W}_1^{\boldsymbol{T}} & \boldsymbol{W}_2\boldsymbol{W}_1^{\boldsymbol{T}} & \cdots & \boldsymbol{W_H}\boldsymbol{W}_1^{\boldsymbol{T}} \\ \boldsymbol{W}_1\boldsymbol{W}_2^{\boldsymbol{T}} & \boldsymbol{W}_2\boldsymbol{W}_2^{\boldsymbol{T}} & \cdots & \boldsymbol{W_H}\boldsymbol{W}_2^{\boldsymbol{T}} \\ \vdots & \vdots & \vdots & \vdots \\ \boldsymbol{W}_1\boldsymbol{W_H^T} & \boldsymbol{W}_2\boldsymbol{W_H^T} & \cdots & \boldsymbol{W_H}\boldsymbol{W_H^T} \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_{\mathrm{H}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{W}_1\boldsymbol{W}_1^{\boldsymbol{T}} \\ \boldsymbol{W}_2\boldsymbol{W}_2^{\boldsymbol{T}} \\ \vdots \\ \boldsymbol{W_H}\boldsymbol{W_H^T} \end{bmatrix} \tag{13}$$

According to the above formula, $(\alpha_1, \alpha_2, \ldots, \alpha_H)$ is determined and normalized:

$$\alpha_h^* = \frac{\alpha_h}{\sum_{h=1}^{H} \alpha_h} \tag{14}$$

Finally, the combination weight is obtained:

$$\boldsymbol{W}^* = \sum_{h=1}^{H} \alpha_h^* \boldsymbol{W_h} \tag{15}$$

3.2.2. Subjective weight-analytic hierarchy process

The main subjective weighting methods are the Delphi method and the analytic hierarchy process (Zhang *et al.* 2022a). The former requires multiple experts and is difficult to implement. The latter not only simplifies the goal but also shares qualitative and quantitative indicators (Xi *et al.* 2010; Chen *et al.* 2014; Wang *et al.* 2015; Feng *et al.* 2017). The evaluation results of the two are also largely the same. Therefore, in this research, the analytic hierarchy process is adopted. The steps are as follows.

1. Establishing a hierarchy

The target layer is the evaluation target. The criterion layer is the criterion for judging the evaluation target. The indicator layer is the subdivided evaluation indicator.

2. Constructing a judgment matrix

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1n} \\ A_{21} & A_{22} & \cdots & A_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & \cdots & A_{nn} \end{bmatrix} \tag{16}$$

where $A_{ii'}$ is the relative importance of i and i' to the upper element.

Based on the comparison of the importance of the indicators, $A_{ii'}$ is shown in Table 2.

3. Hierarchical single sorting and inspection
   (1) Determining the weight

Hierarchical single sorting is based on the judgment matrix to sort the importance. Common methods for calculating weight are the sum product method, power multiplication method, and square root method. In this research, the square root method is used. The formula is as follows (Buckley 1985):

$$W_i = \frac{\sqrt[n]{\prod_{i'=1}^{n} A_{ii'}}}{\sum_{i=1}^{n} \sqrt[n]{\prod_{i'=1}^{n} A_{ii'}}} \tag{17}$$

(2) Calculating the maximum feature root (Wang 2015)

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(\mathrm{A}\boldsymbol{W})_i}{nW_i} \tag{18}$$

(3) Performing an inspection

$$CR = \frac{CI}{RI} \tag{19}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{20}$$

The values of RI are shown in Table 3.

Table 2 | 1–9 Scale method

Scale value	Meaning
1	i is as important as i'
3	i is slightly more important than i'
5	i is significantly more important than i'
7	i has strong importance compared with i'
9	i has extreme importance compared with i'
2, 4, 6, 8	Is the case between the odd numbers of neighbors
Reciprocal	The ratio of the importance of i' to i $A_{i'i} = \frac{1}{A_{ii'}}$

Table 3 | Stochastic consistency index value

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54

The smaller the CI, the greater the consistency. When $CI = 0$, there is complete consistency. When CI is close to zero, there is satisfactory consistency (Razavi *et al.* 2019). Therefore, when $CR < 0.1$, the single sort meets the consistency requirements. Conversely, the judgment matrix must be modified until it passes the consistency inspection. In this way, the weights can be reasonable and the results can be accurate.

4. Performing hierarchical total sorting inspection

CI_i is used as the consistency index of the criterion layer, RI_i is the corresponding stochastic consistency index, and the stochastic consistency ratio of the total sorting of the hierarchy is as follows:

$$CR' = \frac{\sum_{i=1}^{n} W_i' CI_i}{\sum_{i=1}^{n} W_i' RI_i} \tag{21}$$

When $CR' < 0.1$, the total sorting satisfies the consistency. Otherwise, the judgment matrix needs to be reconstructed, and the weights that pass consistency inspection are desirable (He 2008).

3.2.3. Objective weight–variation coefficient method

Objective methods generally include the entropy method and the variation coefficient method. The former is more dependent on the samples. The latter avoids the equal division of weights and makes the result more reasonable. Therefore, in this research, the variation coefficient method is used. The steps are as follows (Jiang 2011):

1. The variation coefficient of the indicator is calculated (Zayed *et al.* 2021):

$$\delta_i = \frac{\sigma_{\mathrm{i}}}{\bar{x}_i} \tag{22}$$

$$\sigma_i = \sqrt{\frac{\sum_{d=1}^{D} (x_{id} - \bar{x}_i)^2}{D}} \tag{23}$$

$$\bar{x}_i = \frac{\sum_{d=1}^{D} x_{id}}{D} \tag{24}$$

where σ_i is the mean variance of the eigenvalue of C_i and $\bar{x}_i$ is the mean value of the eigenvalue of C_i.

2. Calculating the objective weight

$$W_i = \frac{\delta_i}{\sum_{i=1}^{n} \delta_i} \tag{25}$$

3.3. Evaluation indicator

A ship lock is an open complex giant system, and its operational safety can be characterized by multiple subsystems and indicators (Wang & Lee 2001). Each subsystem is finally reflected by the corresponding indicators.

Subsystems can be divided according to the four basic components of the approach channel, lock head, lock chamber, and water transmission system, and the indicators are subdivided in turn. However, the resulting indicator system has many duplicate indicators, resulting in a complex evaluation process. If subsystems are divided into the hydraulic structure, metal structure, hydraulic system, electrical system, and hydraulic power according to the type of specialty, the indicator system and evaluation process can be simplified, and professional safety improvement work can be carried out in a targeted manner according to the evaluation results. The indicators and subsystems safety grade evaluation results of the two ways to divide subsystem are different, but the overall evaluation results of the lock are consistent.

Based on the statistical analysis of the data of multiple representative ship locks, according to the requirements of some evaluation contents in reference (JTS 2019), the operability is considered, the evaluation indicators are sorted out and

Table 4 | List of ship lock operation safety evaluation indicator system

Target layer	Guideline layer	Indicator layer
Operation safety of ship lock	Hydraulic structure	Ratio of damage degree to standard value
		Deformation
		Ratio of crack width to standard value
		Grinding depth
		Carbonization depth
		Ratio of stress to allowable value
		Ratio of seepage flow to standard value
		Ratio of strength to standard value
		Cavitation depth
		Ratio of elastic modulus to standard value
	Metal structure	Ratio of static stress to allowable value
		Fatigue
		Ratio of runout exceeding standard value
		Rust area ratio
		Drift
		Deformation
		Amount of wear
		Lintel ventilation volume
		Ratio of pressure bar clearance exceeding standard value
		Average vibration displacement
		Crack area ratio
		Friction ultrasound
	Hydraulic system	System pressure
		Piston rod deformation
		Running speed
		Piston rod vibration extreme acceleration
		Ratio of opening and closing force to design value
		Ratio of internal leakage amount to standard value
		Aging of the pipeline
		Synchronization error
	Electrical system	Power supply
		Monitor latency
		Communication system stability
		Electronic component failure rate
		Sensor stability
		Navigation signal
		Aging of equipment and facility
		Insulation resistance
		Ground resistance
	Hydraulic power	Water transport characteristic
		Cavitation noise of water flow
		Sonic vibration
		Siltation of the pilot channel
		Ratio of flow velocity in port area to standard value
		Pilot channel water level fluctuation
		Amplitude of upstream and downstream water level pulsation
		Ratio of navigable water depth to standard value

summarized, and then a complete multi-layer evaluation indicator system related to the operation safety of a ship lock is built. A total safety evaluation of the operation of a ship lock is performed, with 5 first-class evaluation indicators and 47 second-class evaluation indicators (Zhang & Li 2020) such as the ratio of the stress to the allowable value, deformation, the ratio of the crack width to the standard value and the ratio of the damage degree to the standard value, etc., to truly reflect the safety status of ship lock operation. The indicator system is shown in Table 4.

3.4. Safety grade

Referring to the division of safety status in pumping stations, sluices, and other engineering fields, combined with the relevant regulations on the operation safety of ship lock in China, such as the 'Technical Code of Maintenance for Navigation Structure', the safety of ship lock operation can be divided into four grades: 'good', 'fair', 'relatively poor', and 'poor'. If these grades are renamed 'normal', 'deterioration', 'early warning', and 'shutdown' (Lu 2019), they can more intuitively characterize the safety status of a lock and guide the corresponding operations. The specific meanings corresponding to each safety grade are shown in Table 5.

N_1, N_2, N_3, and N_4 represent the four grade statuses of 'normal', 'deterioration', 'early warning', and 'shutdown'.

3.5. Evaluation criteria

The grading criteria for the quantitative indicator are determined by its own characteristics, and the qualitative indicator adopts a scoring system. A full score of 100 can be divided equally across the four grades, but the higher the grade is, the more difficult the scoring is, so the score criteria are more reasonable according to Table 6 (Zhang *et al.* 2022b), and the obtained evaluation results are more accurate.

According to the relevant specifications, there are many measurement types of some indicator evaluation standards, and direct adoption increases the amount of calculation. Therefore, harmonizing these criteria with nondimensionalization simplifies the calculations without affecting the results. The safety evaluation criteria for the operation of a ship lock are shown in Table 7.

4. CASE STUDY

This section describes how the operation safety evaluation is carried out in combination with an in-service ship lock in China.

Table 5 | Ship lock operation safety grade and corresponding meaning

Safety grade	Meaning
Grade 1 (Normal)	The actual state and function of the ship lock meet the requirements of current relevant national regulations, norms, and standards, the evaluation indicators are in a normal state, the entire system can operate normally, and the grade of safety is high.
Grade 2 (Deterioration)	Some evaluation indicators show abnormal signs, reaching the deterioration threshold. The function and the actual state of the ship lock cannot fully meet the requirements of the current national regulations, norms, and standards, which may affect the normal use of the ship lock project, and failures are more frequent. The number of overhauls increases significantly and the grade of operation safety is moderate.
Grade 3 (Early warning)	Some evaluation indicators are in an abnormal state, reaching the early warning threshold. There are serious problems that endanger the safety of a ship lock, the number of major failures increases, and the grade of operation safety is low.
Grade 4 (Shutdown)	Some evaluation indicators are in an abnormal state, reaching the shutdown threshold. The function and actual condition of the ship lock cannot meet the requirements of the current national regulations, norms, and standards, and the project has serious safety problems and should be stopped immediately.

Table 6 | Corresponding score criteria at each grade of qualitative indicator

Grade	Grade 1	Grade 2	Grade 3	Grade 4
Score	(90, 100]	(75, 90]	(60, 75]	[0, 60]

Table 7 | Ship lock operation safety evaluation criteria

		Safety status			
Item		**Grade 1 (Normal)**	**Grade 2 (Deterioration)**	**Grade 3 (Early warning)**	**Grade 4 (Shutdown)**
Hydraulic structure	Ratio of damage degree to standard value (%)	[0, 33.33)	[33.33, 100)	[100, 140)	[140, +∞)
	Deformation (mm)	[0, 1.5]	(1.5, 3]	(3, 6]	(6, +∞)
	Ratio of crack width to standard value (%)	[0, 50)	[50, 100)	[100, 140)	[140, +∞)
	Grinding depth (mm)	[0, 1)	[1, 2)	[2, 10)	[10, +∞)
	Carbonization depth (mm)	[0, 1)	[1, 3)	[3, 6)	[6, +∞)
	Ratio of stress to allowable value (%)	[0, 85]	(85, 100]	(100, 115]	(115, +∞)
	Ratio of seepage flow to standard value (%)	[0, 41.67)	[41.67, 100)	[100, 140)	[140, +∞)
	Ratio of strength to standard value (%)	(88.75, 100]	[70, 88.75]	[33.33, 70)	[0, 33.33)
	Cavitation depth (mm)	[0, 0.27)	[0.27, 2)	[2, 5)	[5, +∞)
	Ratio of elastic modulus to standard value (%)	(90, 100]	(75, 90]	(60, 75]	[0, 60]
Metal structure	Ratio of static stress to allowable value (%)	[0, 75)	[75, 80)	[80, 90)	[90, +∞)
	Fatigue	[0, 0.85)	[0.85, 1)	[1, 1.05)	[1.05, 2]
	Ratio of runout exceeding standard value (%)	[−100, 0]	(0, 100)	[100, 133)	[133, +∞)
	Rust area ratio (%)	[0, 0.3)	[0.3, 10)	[10, 11)	[11, +∞)
	Drift (mm)	[0, 3]	(3, 6)	[6, 9)	[9, 12]
	Deformation (mm)	[0, 1.5]	(1.5, 3]	(3, 6]	(6, +∞)
	Amount of wear (mm)	[0, 2.5)	[2.5, 5)	[5, 7.5)	[7.5, 10]
	Lintel ventilation volume (m^3/s)	(0.42, +∞)	(0.37, 0. 42]	(0.33, 0. 37]	[0, 0.33]
	Ratio of pressure bar clearance exceeding standard value (%)	[−62.5, 0]	(0, 100)	[100, 133)	[133, +∞)
	Average vibration displacement (mm)	[0, 0.0508)	[0.0508, 0.254)	[0.254, 0.508]	(0.508, 2]
	Crack area ratio (%)	[0, 0.15)	[0.15, 0.3]	(0.3, 1]	(1, +∞)
	Friction ultrasound	No friction ultrasound	Mild friction ultrasound	Relatively severe friction ultrasound	Severe friction ultrasound
Hydraulic system	System pressure (MPa)	[16, 20]	(14.1, 16)	(3, 14.1]	[0, 3]
	Piston rod deformation (mm)	[0, 1.5]	(1.5, 3]	(3, 6]	(6, +∞)
	Running speed (m/min)	[0, 2)	[2, 4]	(4, 8)	[8, +∞)
	Piston rod vibration extreme acceleration (g)	[0, 0.25)	[0.25, 0. 5]	(0.5, 1)	[1, +∞)
	Ratio of opening and closing force to design value (%)	[0, 40)	[40, 70]	(70, 105)	[105, +∞)
	Ratio of internal leakage amount to standard value (%)	[0, 40)	[40, 100]	(100, 140)	[140, +∞)
	Aging of the pipeline	No aging	Slight aging	Noticeable aging	Severe aging
	Synchronization error (%)	[0, 5)	[5, 15]	(15, 20)	[20, +∞)
Electrical system	Power supply	Normal	Relatively normal	Relatively abnormal	Extremely abnormal
	Monitor latency (s)	[0, 2)	[2, 3)	[3, 6)	[6, +∞)
	Communication system stability	Good	Lower	Obviously lower	Significantly lower
	Electronic component failure rate (%)	[0, 5)	[5, 10)	[10, 30)	[30, 100]
	Sensor stability	Good	Lower	Poor	Extremely poor
	Navigation signal	Stable	Waning	Significantly weakened	Does not meet the requirements

(*Continued*.)

Table 7 | Continued

Item		Safety status Grade 1 (Normal)	Grade 2 (Deterioration)	Grade 3 (Early warning)	Grade 4 (Shutdown)
	Aging of equipment and facility	Intact	Mild aging	Noticeable aging	Severe aging
	Insulation resistance (MΩ)	[5, +∞)	[2, 5)	[0.5, 2)	[0, 0.5)
	Ground resistance (MΩ)	[0, 2)	[2, 4]	(4, 30)	[30, +∞)
Hydraulic power	Water transport characteristic	Good	Relatively good	Relatively poor	Extremely poor
	Cavitation noise of water flow (dB)	[0, 120)	[120, 140)	[140, 160)	[160, +∞)
	Sonic vibration	Extremely weak	Weak	Strong	Extremely strong
	Siltation of the pilot channel	No siltation	Mild siltation	Significant siltation	Severe siltation
	Ratio of flow velocity in port area to standard value (%)	[0, 30)	[30, 100]	(100, 125)	[125, +∞)
	Pilot channel water level fluctuation (m)	[0, 0.4]	(0.4, 0.45)	[0.45, 0. 5]	(0.5, +∞)
	Amplitude of upstream and downstream water level pulsation (m)	[0, 0.1)	[0.1, 0.2)	[0.2, 0. 4]	(0.4, +∞)
	Ratio of navigable water depth to standard value (%)	(150, +∞)	[100, 150]	(47, 100)	[0, 47]

4.1. Classic and node domains

The classic domain and the node domain are determined according to the evaluation criteria of Table 7. The indicator values come from actual measurement and scoring, and their alterations may cause the evaluation indicator, object, and target grade results to be changed in turn.

4.2. Calculation of the correlation degree of a single indicator

The indicator data in Tables 8–12 are substituted into Formulas (4)–(6) to calculate the correlation degree of the single indicator of the second-class indicator, as shown in Tables 13–17.

4.3. Weight with analytic hierarchy process

The judgment matrix and hierarchical sorting of the ship lock operation safety evaluation indicator system are shown in Tables 18–24.

Table 8 | Classic domain, node domain, and indicator value of the second-class indicator of hydraulic structure

Second-class indicator of hydraulic structure	Classic domain N_1	N_2	N_3	N_4	Node domain	The indicator value
Ratio of damage degree to standard value	<0,33.33>	<33.33,100>	<100,140>	<140,200>	<0,200>	14.12
Deformation	<0,1.5>	<1.5,3>	<3,6>	<6,12>	<0,12>	2.2
Ratio of crack width to standard value	<0,50>	<50,100>	<100,140>	<140,200>	<0,29>	21.43
Grinding depth	<0,1>	<1,2>	<2,10>	<10,20>	<0,20>	0.3333
Carbonization depth	<0,1>	<1,3>	<3,6>	<6,12>	<0,12>	0.6667
Ratio of stress to allowable value	<0,85>	<85,100>	<100,115>	<115,130>	<0,130>	0
Ratio of seepage flow to standard value	<0,41.67>	<41.67,100>	<100,140>	<140,200>	<0,200>	33.33
Ratio of strength to standard value	<88.75,100>	<70,88.75>	<33.33,70>	<0,33.33>	<0,100>	25
Cavitation depth	<0,0.27>	<0.27,2>	<2,5>	<5,10>	<0,10>	6
Ratio of elastic modulus to standard value	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	3.4

Table 9 | Classic domain, node domain, and indicator value of the second-class indicator of metal structure

Second-class indicator of metal structure	Classic domain				Node domain	The indicator value
	N_1	N_2	N_3	N_4		
Ratio of static stress to allowable value	<0,75>	<75,80>	<80,90>	<90,100>	<0,100>	85
Fatigue	<0,50>	<50,100>	<100,140>	<140,200>	<0,200>	12
Ratio of runout exceeding standard value	<−100,0>	<0,100>	<100,133>	<133,150>	<−100,150>	29
Rust area ratio	<0,0.3>	<0.3,10>	<10,11>	<11,100>	<0,100>	20
Drift	<0,1.5>	<1.5,3>	<3,6>	<6,12>	<0,12>	5
Deformation	<0,1.5>	<1.5,3>	<3,6>	<6,12>	<0,12>	1.3
Amount of wear	<0,2.5>	<2.5,5>	<5,10>	<10,20>	<0,20>	0
Lintel ventilation volume	<0.42,1>	<0. 37,0.42>	<0.33,0.37>	<0,0.33>	<0,1>	0.25
Ratio of pressure bar clearance exceeding standard value	<−62.5,0>	<0,100>	<100,133>	<133,150>	<−62.5,150>	10
Average vibration displacement	<0,0.0508>	<0.0508,0.254>	<0.254,0.508>	<0.508,1>	<0,1>	0.4
Crack area ratio	<0,0.15>	<0.15,0.3>	<0.3,1>	<1,100>	<0,100>	0.36
Friction ultrasound	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	85

Table 10 | Classic domain, node domain, and indicator value of the second-class indicator of hydraulic system

Second-class indicator of hydraulic system	Classic domain				Node domain	The indicator value
	N_1	N_2	N_3	N_4		
System pressure	<16,20>	<14.1,16>	<3,14.1>	<0,3>	<0,20>	10
Piston rod deformation	<0,1.5>	<1.5,3>	<3,6>	<6,12>	<0,12>	2.2
Running speed	<0,2>	<2,4>	<4,8>	<8,16>	<0,16>	10
Piston rod vibration extreme acceleration	<0,0.25>	<0.25,0.5>	<0.5,1>	<1,2>	<0,2>	0.98
Ratio of opening and closing force to design value	<0,40>	<40,70>	<70,105>	<105,200>	<0,200>	5
Ratio of internal leakage amount to standard value	<0,40>	<40,100>	<100,140>	<140,200>	<0,200>	13
Aging of the pipeline	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	80
Synchronization error	<0,5>	<5,15>	<15,20>	<20,40>	<0,40>	10

Table 11 | Classic domain, node domain, and indicator value of the second-class indicator of electrical system

Second-class indicator of electrical system	Classic domain				Node domain	The indicator value
	N_1	N_2	N_3	N_4		
Power supply	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	20
Monitor latency	<0,2>	<2,3>	<3,6>	<6,7>	<0,7>	1
Communication system stability	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	61
Electronic component failure rate	<0,5>	<5,10>	<10,30>	<30,100>	<0,100>	5
Sensor stability	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	65
Navigation signal	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	85
Aging of equipment and facility	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	80
Insulation resistance	<5,20>	<2,5>	<0.5,2>	<0,0.5>	<0,20>	4
Ground resistance	<0,2>	<2,4>	<4,30>	<30,60>	<0,60>	2

Table 12 | Classic domain, node domain, and indicator value of the second-class indicator of hydraulic power

Second-class indicator of hydraulic power	Classic domain N_1	N_2	N_3	N_4	Node domain	The indicator value
Water transport characteristic	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	95
Cavitation noise of water flow	<0,120>	<120,140>	<140,160>	<160,180>	<0,180>	71
Sonic vibration	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	49
Siltation of the pilot channel	<90,100>	<75,90>	<60,75>	<0,60>	<0,100>	85
Ratio of flow velocity in port area to standard value	<0,30>	<30,100>	<100,125>	<125,200>	<0,200>	100
Pilot channel water level fluctuation	<0,0.4>	<0.4,0.45>	<0.45,0. 5>	<0.5,0.55>	<0,0.55>	0.1
Amplitude of upstream and downstream water level pulsation	<0,0.1>	<0.1,0.2>	<0.2,0.4>	<0.4,0.8>	<0,0.8>	0.8
Ratio of navigable water depth to standard value	<150,200>	<100,150>	<47,100>	<0,47>	<0,200>	200

Table 13 | Correlation degree of a single indicator of the second-class indicator of hydraulic structure

Second-class indicator of hydraulic structure	N_1	N_2	N_3	N_4	Max	Grade
Ratio of damage degree to standard value	0.4236	−0.5764	−0.8588	−0.8991	0.4236	1
Deformation	−0.2414	0.4667	−0.2667	−0.6333	0.4667	2
Ratio of crack width to standard value	0.4286	−0.5714	−0.7857	−0.8469	0.4286	1
Grinding depth	0.3333	−0.6667	−0.8334	−0.9667	0.3333	1
Carbonization depth	0.3333	−0.3333	−0.7778	−0.8889	0.3333	1
Ratio of stress to allowable value	0	−1	−1	−1	0	1
Ratio of seepage flow to standard value	0.2001	−0.2001	−0.6667	−0.7619	0.2001	1
Ratio of strength to standard value	−0.7183	−0.6429	−0.2499	0.2499	0.2499	4
Cavitation depth	−0.5889	−0.5	−0.2	0.2	−0.5889	4
Ratio of elastic modulus to standard value	−0.9622	−0.9547	−0.9433	0.0567	0.0567	4

Table 14 | Correlation degree of a single indicator of the second-class indicator of metal structure

Second-class indicator of metal structure	N_1	N_2	N_3	N_4	Max	Grade
Ratio of static stress to allowable value	−0.4	−0.25	0.5	−0.25	0.5	3
Fatigue	0.24	−0.76	−0.88	−0.9143	0.24	1
Ratio of runout exceeding standard value	−0.1933	0.29	−0.3698	−0.4622	0.29	2
Rust area ratio	−0.4962	−0.3333	−0.3103	0.1011	0.1011	4
Drift	−0.4118	−0.2857	0.3333	−0.1667	0.3333	3
Deformation	0.1333	−0.1333	−0.5667	−0.7833	01333	1
Amount of wear	0	−1	−1	−1	0	1
Lintel ventilation volume	−0.4048	−0.3243	−0.2424	0.2424	0.2424	4
Ratio of pressure bar clearance exceeding standard value	−0.1212	0.1	−0.5538	−0.6292	0.1	2
Average vibration displacement	−0.4661	−0.2674	0.4252	−0.2126	0.4252	3
Crack area ratio	−0.3684	−0.1429	0.0857	−0.64	0.0857	3
Friction ultrasound	−0.25	0.3333	−0.4	−0.625	0.3333	2

Table 15 | Correlation degree of a single indicator of the second -class indicator of hydraulic system

Second-class indicator of hydraulic system	N_1	N_2	N_3	N_4	Max	Grade
System pressure	−0.375	−0.2908	0.3694	−0.4118	0.3694	3
Piston rod deformation	−0.2414	0.4667	−0.2667	−0.6333	0.4667	2
Running speed	−0.5714	−0.5	−0.25	0.25	0.25	4
Piston rod vibration extreme acceleration	−0.4269	−0.3288	0.04	−0.02	0.04	3
Ratio of opening and closing force to design value	0.125	−0.875	−0.9286	−0.9524	0.125	1
Ratio of internal leakage amount to standard value	0.325	−0.675	−0.87	−0.9071	0.325	1
Aging of the pipeline	−0.3333	0.3333	−0.2	−0.5	0.3333	2
Synchronization error	−0.3333	0.5	−0.3333	−0.5	0.5	2

Table 16 | Correlation degree of a single indicator of the second-class indicator of electrical system

Second-class indicator of electrical system	N_1	N_2	N_3	N_4	Max	Grade
Power supply	−0.7778	−0.7333	−0.6667	0.3333	0.3333	4
Monitor latency	0.5	−0.5	−0.6667	−0.8333	0.5	1
Communication system stability	−0.4265	−0.2642	0.0667	−0.025	0.0667	3
Electronic component failure rate	0	0	−0.5	−0.8333	0	2
Sensor stability	−0.4167	−0.2222	0.3333	−0.125	0.3333	3
Navigation signal	−0.25	0.3333	−0.4	−0.625	0.3333	2
Aging of equipment and facility	−0.3333	0.3333	−0.2	−0.5	0.3333	2
Insulation resistance	−0.2	0.3333	−0.3333	−0.4667	0.3333	2
Ground resistance	0	0	−0.5	−0.9333	0	2

Table 17 | Correlation degree of a single indicator of the second-class indicator of hydraulic power

Second-class indicator of hydraulic power	N_1	N_2	N_3	N_4	Max	Grade
Water transport characteristic	0.5	−0.5	−0.8	−0.875	0.5	1
Cavitation noise of water flow	0.4083	−0.4083	−0.4929	−0.5562	0.4083	1
Sonic vibration	−0.4556	−0.3467	−0.1833	0.1833	0.1833	4
Siltation of the pilot channel	−0.25	0.3333	−0.4	−0.625	0.3333	2
Ratio of flow velocity in port area to standard value	−0.4118	0	0	−0.2	0	3
Pilot channel water level fluctuation	0.25	−0.75	−0.7778	−0.8	0.25	1
Amplitude of upstream and downstream water level pulsation	−1	−1	−1	0	0	4
Ratio of navigable water depth to standard value	0	−1	−1	−1	0	1

4.4. Weight with variation coefficient method

The variation coefficient and weight of each indicator are calculated according to Formulas (22) to (25). The final result is shown in Table 25. Indicators data are included in the supplementary file.

4.5. Game theory combination weighting method

Compared with the above result, the weight distribution of the two methods is different, so the weights need to be optimized.

Table 18 | Judgment matrix and hierarchical single sorting of operation safety first-class indicator

Operation safety	Hydraulic structure	Metal structure	Hydraulic system	Electrical system	Hydraulic power	W_i	Sort	Inspection
Hydraulic structure	1	$\frac{1}{2}$	3	4	2	0.2634	2	$\lambda_{\max} = 5.068$ $CI = 0.017$ $RI = 1.12$ $CR = 0.0152 < 0.1$
Metal structure	2	1	4	5	3	0.4174	1	
Hydraulic system	$\frac{1}{3}$	$\frac{1}{4}$	1	2	$\frac{1}{2}$	0.0975	4	
Electrical system	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{2}$	1	$\frac{1}{3}$	0.0615	5	
Hydraulic power	$\frac{1}{2}$	$\frac{1}{3}$	2	3	1	0.1602	3	

For the base weight set $\{\boldsymbol{W_1}, \boldsymbol{W_2}\}$, $\boldsymbol{W}_1\boldsymbol{W}_1^{\boldsymbol{T}} = 0.0475$, $\boldsymbol{W}_2\boldsymbol{W}_1^{\boldsymbol{T}} = \boldsymbol{W}_1\boldsymbol{W}_2^{\boldsymbol{T}} = 0.0246$, $\boldsymbol{W}_2\boldsymbol{W}_2^{\boldsymbol{T}} = 0.0286$, and weight vector set (12) can be written as follows:

$$\begin{bmatrix} 0.0475 & 0.0246 \\ 0.0246 & 0.0286 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} 0.0475 \\ 0.0286 \end{bmatrix} \tag{26}$$

The optimal solutions of Formula (26) are $\alpha_1 = 0\ 8689$ and $\alpha_2 = 0.2534$, which are then normalized, and the final results are $\alpha_1^* = 0.7742$ and $\alpha_2^* = 0.2258$.

The final combination weight can be derived from Formula (15):

$\boldsymbol{W}^*$= (0.0211,0.0498,0.0656,0.0247,0.0128,0.0123,0.0106,0.0078,0.0363,0.0061,0.0376,0.061,0.0084,0.0134,0.0067,0.0704,0.0205,0.0232,0.0094,0.0311,0.0909,0.0108,0.0047,0.0293,0.011,0.0209,0.0137,0.0071,0.0127,0.0106,0.0053,0.0052,0.0122,0.0265,0.0105,0.0054,0.0095,0.0103,0.0155,0.0178,0.0445,0.0365,0.0035,0.0118,0.0086,0.0112,0.0252)

4.6. Calculation of the comprehensive correlation degree of multiple indicators and the rating

The correlation degree of a single indicator in Tables 13–17 and the calculated weight are substituted into Formulas (7)–(9) to calculate the comprehensive correlation degree of multiple indicators. The final grade is evaluated as Table 26.

The result shows that the operation safety grade of the ship lock belongs to the first grade (normal state), and all the first-class indicators belong to the first grade, except for the hydraulic system and electrical system, which belong to the second grade (deterioration state). Among the second-class indicators, special attention should be paid to the following: the ratio of the strength to the standard value, the cavitation depth and the ratio of the elastic modulus to the standard value of the hydraulic structure; the rust area ratio and the lintel ventilation volume of the metal structure; the running speed of the hydraulic system; the power supply of the electrical system; and the sonic vibration and the amplitude of the upstream and downstream water level pulsation of the hydraulic power belonging to the fourth grade (shutdown state).

5. DISCUSSION AND CONCLUSION

The operation safety evaluation of an in-service ship lock is extremely essential and has significant social and economic benefits. In this study, a ship lock operation safety evaluation system was systematically discussed. The safety accident examples of ship locks were counted, and the operation safety evaluation scheme suitable for a ship lock was formulated in a targeted manner. The safety evaluation indicator system of a ship lock was constructed and the evaluation method and process of ship lock operation safety based on extension theory were proposed to provide a basis for the safety evaluation of ship locks. The following conclusions were drawn.

Due to the complexity of a ship lock, the weight of the safety indicator could not be determined using a single weighting method. The combination weighting method based on the game theory used in this study could apply to the weight fusion of a ship lock operation safety indicator. Comparing the results of three types of weights, it was found that the combination

Table 19 | Judgment matrix and hierarchical single sorting of hydraulic structure second-class indicator

Hydraulic structure	**Ratio of damage degree to standard value**	**Deformation**	**Ratio of crack width to standard value**	**Grinding depth**	**Carbonization depth**	**Ratio of stress to allowable value**	**Ratio of seepage flow to standard value**	**Ratio of strength to standard value**	**Cavitation depth**	**Ratio of elastic modulus to standard value**	W_i	**Sort**	**Inspection**
Ratio of damage degree to standard value	1	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{2}$	2	6	3	4	$\frac{1}{3}$	5	0.0771	5	$\lambda_{\max} = 10.5513$ $CI = 0.0612$ $RI = 1.49$ $CR = 0.0411 < 0.1$
Deformation	4	1	$\frac{1}{2}$	3	5	9	6	7	2	8	0.2164	2	
Ratio of crack width to standard value	5	2	1	4	6	9	7	8	3	9	0.2889	1	
Grinding depth	2	$\frac{1}{3}$	$\frac{1}{4}$	1	3	7	4	5	$\frac{1}{2}$	6	0.11	4	
Carbonization depth	$\frac{1}{2}$	$\frac{1}{5}$	$\frac{1}{6}$	$\frac{1}{3}$	1	5	2	3	$\frac{1}{4}$	4	0.0539	6	
Ratio of stress to allowable value	$\frac{1}{6}$	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{7}$	$\frac{1}{5}$	1	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{8}$	$\frac{1}{2}$	0.0144	10	
Ratio of seepage flow to standard value	$\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{7}$	$\frac{1}{4}$	$\frac{1}{2}$	4	1	2	$\frac{1}{5}$	3	0.0378	7	
Ratio of strength to standard value	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{8}$	$\frac{1}{5}$	$\frac{1}{3}$	3	$\frac{1}{2}$	1	$\frac{1}{6}$	2	0.0267	8	
Cavitation depth	3	$\frac{1}{2}$	$\frac{1}{3}$	2	4	8	5	6	1	7	0.1556	3	
Ratio of elastic modulus to standard value	$\frac{1}{5}$	$\frac{1}{8}$	$\frac{1}{9}$	$\frac{1}{6}$	$\frac{1}{4}$	2	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{7}$	1	0.0192	9	

Table 20 | Judgment matrix and hierarchical single sorting of metal structure second-class indicator

Metal structure	Ratio of static stress to allowable value	Fatigue	Ratio of runout exceeding standard value	Rust area ratio	Drift	Deformation	Amount of wear	Lintel ventilation volume	Ratio of pressure bar clearance exceeding standard value	Average vibration displacement	Crack area ratio	Friction ultrasound	W_i	Sort	Inspection
Ratio of static stress to allowable value	1	$\frac{1}{2}$	7	5	9	$\frac{1}{3}$	4	3	8	2	$\frac{1}{4}$	6	0.1131	4	$\lambda_{\max} = 12.995$ $CI = 0.0904$ $RI = 1.54$ $CR = 0.0587 < 0.1$
Fatigue	2	1	8	6	9	$\frac{1}{2}$	5	4	9	3	$\frac{1}{3}$	7	0.1524	3	
Ratio of runout exceeding standard value	$\frac{1}{7}$	$\frac{1}{8}$	1	$\frac{1}{3}$	3	$\frac{1}{9}$	$\frac{1}{4}$	$\frac{1}{5}$	2	$\frac{1}{6}$	$\frac{1}{9}$	$\frac{1}{2}$	0.0169	10	
Rust area ratio	$\frac{1}{5}$	$\frac{1}{6}$	3	1	5	$\frac{1}{7}$	$\frac{1}{2}$	$\frac{1}{3}$	4	$\frac{1}{4}$	$\frac{1}{8}$	2	0.0312	8	
Drift	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{1}{3}$	$\frac{1}{5}$	1	$\frac{1}{9}$	$\frac{1}{6}$	$\frac{1}{7}$	$\frac{1}{2}$	$\frac{1}{8}$	$\frac{1}{9}$	$\frac{1}{4}$	0.0101	12	
Deformation	3	2	9	7	9	1	6	5	9	4	$\frac{1}{2}$	8	0.2006	2	
Amount of wear	$\frac{1}{4}$	$\frac{1}{5}$	4	2	6	$\frac{1}{6}$	1	$\frac{1}{2}$	5	$\frac{1}{3}$	$\frac{1}{7}$	3	0.0431	7	
Lintel ventilation volume	$\frac{1}{3}$	$\frac{1}{4}$	5	3	7	$\frac{1}{5}$	2	1	6	$\frac{1}{2}$	$\frac{1}{6}$	4	0.0596	6	
Ratio of pressure bar clearance exceeding standard value	$\frac{1}{8}$	$\frac{1}{9}$	$\frac{1}{2}$	$\frac{1}{4}$	2	$\frac{1}{9}$	$\frac{1}{5}$	$\frac{1}{6}$	1	$\frac{1}{7}$	$\frac{1}{9}$	$\frac{1}{3}$	0.0128	11	
Average vibration displacement	$\frac{1}{2}$	$\frac{1}{3}$	6	4	8	$\frac{1}{4}$	3	2	7	1	$\frac{1}{5}$	5	0.0823	5	
Crack area ratio	4	3	9	8	9	2	7	6	9	5	1	9	0.2552	1	
Friction ultrasound	$\frac{1}{6}$	$\frac{1}{7}$	2	$\frac{1}{2}$	4	$\frac{1}{8}$	$\frac{1}{3}$	$\frac{1}{4}$	3	$\frac{1}{5}$	$\frac{1}{9}$	1	0.0227	9	

Table 21 | Judgment matrix and hierarchical single sorting of hydraulic system second-class indicator

Hydraulic system	System pressure	Piston rod deformation	Running speed	Piston rod vibration extreme acceleration	Ratio of opening and closing force to design value	Ratio of internal leakage amount to standard value	Aging of the pipeline	Synchronization error	W_i	Sort	Inspection
System pressure	1	$\frac{1}{7}$	$\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{2}$	2	$\frac{1}{5}$	$\frac{1}{4}$	0.0327	7	$\lambda_{\max} = 8.2877$ $CI = 0.0411$ $RI = 1.41$ $CR = 0.0292 < 0.1$
Piston rod deformation	7	1	5	2	6	8	3	4	0.328	1	
Running speed	3	$\frac{1}{5}$	1	$\frac{1}{4}$	2	4	$\frac{1}{3}$	$\frac{1}{2}$	0.0713	5	
Piston rod vibration extreme acceleration	6	$\frac{1}{2}$	4	1	5	7	2	3	0.2319	2	
Ratio of opening and closing force to design value	2	$\frac{1}{6}$	$\frac{1}{2}$	$\frac{1}{5}$	1	3	$\frac{1}{4}$	$\frac{1}{3}$	0.0479	6	
Ratio of internal leakage amount to standard value	$\frac{1}{2}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{3}$	1	$\frac{1}{6}$	$\frac{1}{5}$	0.0231	8	
Aging of the pipeline	5	$\frac{1}{3}$	3	$\frac{1}{2}$	4	6	1	2	0.1585	3	
Synchronization error	4	$\frac{1}{4}$	2	$\frac{1}{3}$	3	5	$\frac{1}{2}$	1	0.1066	4	

Table 22 | Judgment matrix and hierarchical single sorting of electrical system second-class indicator

Electrical system	**Power supply**	**Monitor latency**	**Communication system stability**	**Electronic component failure rate**	**Sensor stability**	**Navigation signal**	**Aging of equipment and facility**	**Insulation resistance**	**Ground resistance**	w_i	**Sort**	**Inspection**
Power supply	1	3	$\frac{1}{6}$	$\frac{1}{7}$	$\frac{1}{5}$	2	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	0.0352	7	$\lambda_{\max} = 9.4004$ $CI = 0.05$ $RI = 1.46$ $CR = 0.0343 < 0.1$
Monitor latency	$\frac{1}{3}$	1	$\frac{1}{8}$	$\frac{1}{9}$	$\frac{1}{7}$	$\frac{1}{2}$	$\frac{1}{6}$	$\frac{1}{5}$	$\frac{1}{4}$	0.0179	9	
Communication system stability	6	8	1	$\frac{1}{2}$	2	7	3	4	5	0.2235	2	
Electronic component failure rate	7	9	2	1	3	8	4	5	6	0.3081	1	
Sensor stability	5	7	$\frac{1}{2}$	$\frac{1}{3}$	1	6	2	3	4	0.157	3	
Navigation signal	$\frac{1}{2}$	2	$\frac{1}{7}$	$\frac{1}{8}$	$\frac{1}{6}$	1	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$	0.0247	8	
Aging of equipment and facility	4	6	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{2}$	5	1	2	3	0.1084	4	
Insulation resistance	3	5	$\frac{1}{4}$	$\frac{1}{5}$	$\frac{1}{3}$	4	$\frac{1}{2}$	1	2	0.0743	5	
Ground resistance	2	4	$\frac{1}{5}$	$\frac{1}{6}$	$\frac{1}{4}$	3	$\frac{1}{3}$	$\frac{1}{2}$	1	0.0509	6	

Table 23 | Judgment matrix and hierarchical single sorting of hydraulic power second-class indicator

Hydraulic power	Water transport characteristic	Cavitation noise of water flow	Sonic vibration	Siltation of the pilot channel	Ratio of flow velocity in port area to standard value	Pilot channel water level fluctuation	Amplitude of upstream and downstream water level pulsation	Ratio of navigable water depth to standard value	W_i	Sort	Inspection
Water transport characteristic	1	$\frac{1}{4}$	$\frac{1}{3}$	5	2	4	3	$\frac{1}{2}$	0.1066	4	$\lambda_{\max} = 8.2877$ $CI = 0.0411$ $RI = 1.41$ $CR = 0.0292 < 0.1$
Cavitation noise of water flow	4	1	2	8	5	7	6	3	0.328	1	
Sonic vibration	3	$\frac{1}{2}$	1	7	4	6	5	2	0.2319	2	
Siltation of the pilot channel	$\frac{1}{5}$	$\frac{1}{8}$	$\frac{1}{7}$	1	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{6}$	0.0231	8	
Ratio of flow velocity in port area to standard value	$\frac{1}{2}$	$\frac{1}{5}$	$\frac{1}{4}$	4	1	3	2	$\frac{1}{3}$	0.0713	5	
Pilot channel water level fluctuation	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{6}$	2	$\frac{1}{3}$	1	$\frac{1}{2}$	$\frac{1}{5}$	0.0327	7	
Amplitude of upstream and downstream water level pulsation	$\frac{1}{3}$	$\frac{1}{6}$	$\frac{1}{5}$	3	$\frac{1}{2}$	2	1	$\frac{1}{4}$	0.0479	6	
Ratio of navigable water depth to standard value	2	$\frac{1}{3}$	$\frac{1}{2}$	6	3	5	4	1	0.1585	3	

Table 24 | Hierarchical total sorting

Indicator layer	**Hydraulic structure 0.2634**	**Metal structure 0.4174**	**Hydraulic system 0.0975**	**Electrical system 0.0615**	**Hydraulic power 0.1602**	W_i	**Sort**	**Inspection**
Ratio of damage degree to standard value	0.0771					0.0203	16	$CR = 0.0454 < 0.1$
Deformation	0.2164					0.057	5	
Ratio of crack width to standard value	0.2889					0.0761	3	
Grinding depth	0.11					0.029	12	
Carbonization depth	0.0539					0.0142	21	
Ratio of stress to allowable value	0.0144					0.0038	40	
Ratio of seepage flow to standard value	0.0378					0.0099	26	
Ratio of strength to standard value	0.0267					0.007	31	
Cavitation depth	0.1556					0.041	8	
Ratio of elastic modulus to standard value	0.0192					0.0051	36	
Ratio of static stress to allowable value		0.1131				0.0472	7	
Fatigue		0.1524				0.0636	4	
Ratio of runout exceeding standard value		0.0169				0.0071	30	
Rust area ratio		0.0312				0.013	23	
Drift		0.0101				0.0042	39	
Deformation		0.2006				0.0837	2	
Amount of wear		0.0431				0.018	18	
Lintel ventilation volume		0.0596				0.0249	14	
Ratio of pressure bar clearance exceeding standard value		0.0128				0.0053	34	
Average vibration displacement		0.0823				0.0344	10	
Crack area ratio		0.2552				0.1065	1	
Friction ultrasound		0.0227				0.0095	28	
System pressure			0.0327			0.0032	42	
Piston rod deformation			0.328			0.032	11	
Running speed			0.0713			0.0069	32	
Piston rod vibration extreme acceleration			0.2319			0.0226	15	
Ratio of opening and closing force to design value			0.0479			0.0047	37	
Ratio of internal leakage amount to standard value			0.0231			0.0023	44	
Aging of the pipeline			0.1585			0.0154	20	
Synchronization error			0.1066			0.0104	25	
Power supply				0.0352		0.0022	45	
Monitor latency				0.0179		0.0011	47	
Communication system stability				0.2235		0.0137	22	

(*Continued.*)

Table 24 | Continued

Indicator layer	Hydraulic structure 0.2634	Metal structure 0.4174	Hydraulic system 0.0975	Electrical system 0.0615	Hydraulic power 0.1602	W_i	Sort	Inspection
Electronic component failure rate				0.3081		0.019	17	
Sensor stability				0.157		0.0096	27	
Navigation signal				0.0247		0.0015	46	
Aging of equipment and facility				0.1084		0.0067	33	
Insulation resistance				0.0743		0.0046	38	
Ground resistance				0.0509		0.0031	43	
Water transport characteristic					0.1066	0.0171	19	
Cavitation noise of water flow					0.328	0.0526	6	
Sonic vibration					0.2319	0.037	9	
Siltation of the pilot channel					0.0231	0.0037	41	
Ratio of flow velocity in port area to standard value					0.0713	0.0114	24	
Pilot channel water level fluctuation					0.0327	0.0053	35	
Amplitude of upstream and downstream water level pulsation					0.0479	0.0077	29	
Ratio of navigable water depth to standard value					0.1585	0.0254	13	

Table 25 | Weight of operation safety evaluation indicator based on the variation coefficient method

		Indicator layer	
Target layer	Guideline layer	Indicator	Weight
Operation safety	Hydraulic structure	Ratio of damage degree to standard value	0.0239
		Deformation	0.0253
		Ratio of crack width to standard value	0.0297
		Grinding depth	0.0102
		Carbonization depth	0.0078
		Ratio of stress to allowable value	0.0413
		Ratio of seepage flow to standard value	0.0129
		Ratio of strength to standard value	0.0104
		Cavitation depth	0.0202
		Ratio of elastic modulus to standard value	0.0098
	Metal structure	Ratio of static stress to allowable value	0.0046
		Fatigue	0.052
		Ratio of runout exceeding standard value	0.0132
		Rust area ratio	0.0148
		Drift	0.0153
		Deformation	0.0245
		Amount of wear	0.0293
		Lintel ventilation volume	0.0175
		Ratio of pressure bar clearance exceeding standard value	0.0233
		Average vibration displacement	0.0197
		Crack area ratio	0.0371
		Friction ultrasound	0.0154
	Hydraulic system	System pressure	0.0098
		Piston rod deformation	0.0202
		Running speed	0.025

(*Continued.*)

Table 25 | Continued

Target layer	Guideline layer	Indicator layer Indicator	Weight
		Piston rod vibration extreme acceleration	0.0151
		Ratio of opening and closing force to design value	0.0448
		Ratio of internal leakage amount to standard value	0.0237
		Aging of the pipeline	0.0032
		Synchronization error	0.0113
	Electrical system	Power supply	0.0161
		Monitor latency	0.0193
		Communication system stability	0.0069
		Electronic component failure rate	0.0522
		Sensor stability	0.0135
		Navigation signal	0.0189
		Aging of equipment and facility	0.0191
		Insulation resistance	0.0298
		Ground resistance	0.0577
	Hydraulic power	Water transport characteristic	0.0203
		Cavitation noise of water flow	0.017
		Sonic vibration	0.0342
		Siltation of the pilot channel	0.0028
		Ratio of flow velocity in port area to standard value	0.0131
		Pilot channel water level fluctuation	0.0202
		Amplitude of upstream and downstream water level pulsation	0.023
		Ratio of navigable water depth to standard value	0.0246

Table 26 | Extension evaluation result of the operation safety of a certain ship lock

Item		N_1	N_2	N_3	N_4	Max	Grade
Guideline layer	Hydraulic structure	0.0274	−0.3664	−0.5982	−0.6156	0.0274	1
	Metal structure	−0.165	−0.297	−0.2465	−0.5641	−0. 165	1
	Hydraulic system	−0.2526	−0.0668	−0.2999	−0.4482	−0.0668	2
	Electrical system	−0.1762	−0.0365	−0.3104	−0.5341	−0.0365	2
	Hydraulic power	−0.0268	−0.5116	−0.549	−0.442	−0.0268	1
Target layer	Operation safety	−0.1062	−0.2968	−0.3938	−0.5416	−0.1062	1

weighting method was between the analytic hierarchy process and the variation coefficient method, showing that it combined the advantages of the two methods and made the results more accurate.

Notably, the limitation of this study was that the indicator system was too large, which led to very low weights and weakened the importance of key indicators. This could be improved by reducing the dimensionality and giving key indicators ‘one veto power’. In the future, lock safety evaluation should develop in the direction of real-time intelligence.

AUTHOR CONTRIBUTIONS

All authors contributed to the study’s conception and design. Material preparation, data collection, and analysis were performed by Yaan Hu, Xin Wang, and Mingjun Diao. The first draft of the manuscript was written by Junman Li and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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