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A Comprehensive Evaluation Method for the Service Status of Groins in Waterways Based on an AHP-Improved CRITIC Combination Weighting Optimization Model

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Abstract: A comprehensive evaluation model that combines an analytical hierarchy process (AHP) method and the improved version of the Criteria Importance Through Inter-criteria Correlation (CRITIC) method is proposed to solve integrated assessment problems related to the service status of groins in waterways. In view of the influencing factors and functional characteristics of damaged groins for waterway regulation, a waterway groin service status (WGSS) evaluation index system with a hierarchical structure was constructed using target-criteria elements. Additionally, based on the multi-attribute characteristics of the indicators, standards for rating and assigning values to elemental indicators were developed. Considering that traditional empowerment methods are rather one-sided and limited, an AHP-improved CRITIC method combination assigning optimization model was established based on the least squares principle, and the optimal combination weights were solved by the Lagrange multiplier method. The reliability and applicability of the model were tested by successfully applying the evaluation model to the comprehensive evaluation of the service status of spur dikes in the upper reaches of the Yangtze River. The results showed that the combined weights that were calculated by the AHP and the improved CRITIC optimization model were able to reflect both subjective and objective information, which makes up for the shortcomings of a single assignment method, and the weights assigned to the service status evaluation indexes for groins were reasonable. The comprehensive evaluation method to determine the service status of groins proposed in this paper was more accurate than the traditional evaluation method with subjective assignment and provided a scientific basis for decision making to maintain the sustainability of groin function.

Keywords: waterway infrastructure; service status of groins; comprehensive evaluation; multiple-criteria decision making (MCDM); combined weights; AHP; improved CRITIC method; least squares optimization



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1. Introduction

Waterway traffic infrastructure is a fundamental component of today's globally interconnected world and is fundamental to guarantee smooth waterway transportation [1]. Spur dikes used for waterway regulation are the most commonly used waterway traffic infrastructure. Their main function is to increase the size of the waterway and to improve the navigable water flow conditions by restricting the water flow and scouring the waterway [2]. Due to comprehensive factors such as structural characteristics, material composition, and complex water and sand environments, the dam body is often damaged and scoured, resulting in the service state of the spur dikes changing over time [3,4].

In recent years, there has been an increasing interest in risk evaluation issues concerning groin structures in waterways. Wang et al. [5] used fuzzy theory to evaluate the safety and stability of regulating structures in a channel. Yu et al. [6] analyzed the factors influencing the maximum scour depth of the head of a groin, and used the extreme difference analysis method to evaluate the effects of the weights of different head types, different dam lengths, and different pick angles on the safety of spur dikes. Zhang et al. [7] provided technical support for scour pit protection by studying the effect of the spur dike angle on the evolution of scour pit morphology at the head of a dam. Wen et al. [8] classified the safety level of dam sub-indicators by regression analysis and carried out a comprehensive evaluation of the performance of panel rockfill dams using a fuzzy identification model. Wu et al. [9] proposed a comprehensive evaluation method for the service status of dams in response to the large number of diseased dams, high dams, and extra-high dams in China.

The timely tracking, monitoring, and evaluation of the service status of groins can provide a management system that provides a basis for waterway maintenance decisions, and therefore, the comprehensive evaluation of the service status of groins has become an important part of waterway safety and maintenance management [10]. The water damage caused to spur dikes under the joint action of water flow and sediment is very complicated, and it is still impossible to explain and describe its intrinsic mechanism accurately, but projects need to know the level of water damage affecting spur dikes at any given time in order to manage and maintain it efficiently. At present, the methods through which waterway infrastructure can be evaluated are still relatively traditional, and most of them are only qualitative level. Although on-site inspection is more direct and effective, relying on manual discrimination entirely can only yield relatively rough results and does not facilitate unified coordination and management. Therefore, comprehensive evaluations using real-time information of specific indicators is a good way to cope with this. When the variable relationships and interaction mechanisms among the indicators are not known, only the real-time status information of the indicators needs to be collected to understand the current service status of the groin, thus providing a basis for making maintenance decisions for waterway facilities. The research in this paper is carried out precisely to solve practical management problems. The application of scientific and accurate evaluation methods for the management of waterway infrastructure will probably become a demand and development trend in the future, and, in fact, Chinese waterway management authorities are carrying out the construction and management of intelligent waterways [11,12], and the work in this paper is a useful exploration of the construction of intelligent waterways.

In studies on the evaluation indexes of groins, most of the literature only considers some indicators of the service state of spur dikes, but it is rare to find a set of indicators for evaluating the service state of a groin that are both suitable and comprehensive. Chen et al. [13] used the width and width-to-depth ratio of the river section at the design-minimum navigable water level as the evaluation index to determine the function of spur dike groups. The index referred to the functions of water bundling and sand flushing, and evaluated and predicted them using an SVM model. Li et al. [10] evaluated the functional condition of spur dikes using three indicators: water and sand control; flow diversion and navigation optimization; and the structural condition of spur dikes according to their levels of partial damage and overall damage and constructed a technical condition evaluation index system for waterway regulation buildings. Wang et al. [14] used the back slope of a local scour pit as a reliability index to evaluate the erosion stability of the groin. Han et al. [15] conducted a quantitative evaluation of the degree of water damage degree in spur dikes by using the water damage volume ratio as an evaluation index to determine the safety of rock-rippling groins.

To evaluate the service status of spur dikes accurately, it is necessary to study the contribution and influence of each indicator to it, rank the priority of the evaluation indicators, and assign weights. Essentially, this type of problem is a multi-attribute decision problem and can be solved by the multi-attribute decision-making (MCDM) method. There are very many MCDM methods that have been researched and developed by previous authors, such

as AHP, the analytical network process (ANP), the best–worst method (BWM), CRITIC, the entropy weight method (EWM), fuzzy methods, the technique for order of preference by similarity to ideal solution (TOPSIS), VišeKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), etc. [16,17]. AHP is one of the classical representatives and has been widely used in various fields and has achieved impressive results [18,19]. However, in the face of specific problems. AHP also reveals many limitations, so researchers have proposed many improved multi-criteria decision-making methods based on “hierarchical analysis”, such as those that combine the AHP method with the Delphi method to solve the problem of selecting evaluation indicators in the case of too many complex influencing factors [20,21], that combine fuzzy methods to solve the problem of measuring the uncertainty of evaluation objects [22,23], etc. The core idea of AHP is to construct a two-comparison judgment matrix through expert scoring and to find the set of index weights that maintain the consistency, so the biggest limitation is this method’s subjective dependence.

The traditional method of determining the weight of the indicators used to evaluate waterway facilities mostly adopts subjective weighting methods, such as the trial algorithm used in studies [10,13] and the AHP method used in studies [8,9], both of which were based on expert scoring. These methods have too many subjective influencing factors and greater arbitrariness, resulting in the lack of the theoretical support and objective basis required for the weight calculation results, which ultimately affects the accuracy of the evaluation results and their credibility. Therefore, how to accurately assign weights to each evaluation index has always been a difficult problem in the evaluation process.

Many researchers have tried to combine objective weighting methods with AHP to obtain a combination model comprising subjective and objective weights to improve the subjective limitations of a single weighting method [24–27]. Objective weighting methods include EWM, CRITIC, standard deviation (SD), the coefficient of variation (CV), improved CRITIC, etc. Their basic idea is to use the information carried by the data themselves to calculate the degree of influence of each index on the total score [28,29]. Among them, the improved CRITIC method has been optimized and has been improved on the basis of the previous methods, and it can effectively reduce the influence of errors caused by different dimensions and orders of magnitude and make the weight calculation results more objective and reasonable [29]. Therefore, according to the characteristics of the research object, this paper chooses to combine and integrate the AHP method and the improved CRITIC method to solve weight distribution problems in spur dike evaluation indexes.

This paper proposes a more scientific state evaluation method for the service state of groins in waterways and mainly includes a system of comprehensive evaluation indexes and a subject-objective combination weighting optimization model. This method was successfully applied to a comprehensive evaluation of a typical groin in the upper Yangtze River channel. This method can provide an accurate quantification and comprehensive evaluation of the service status of groins, thus providing a basis for the maintenance of and decision-making for channel infrastructure.

2. Groin Service State Evaluation Index System

2.1. Connotation of Groin’s Service State Evaluation

The service status of waterway groins should include two aspects: the safety status of the dam body and the functioning status. Obviously, the safety status of the dam body may affect the remediation function of the spur dike.

The safety state of the dam body mainly depends on the damage to the different parts comprising the outside of the dam body, which is divided into the dam surface, side slope, head, body, root, and scour pit [4]. The common forms of structural failure found in spur dikes in practice are shown in Figure 1a–e. The safety status of the dam body can be inspected from several aspects, such as whether the dam body is missing, whether the appearance is deformed, and whether the structure is stable.

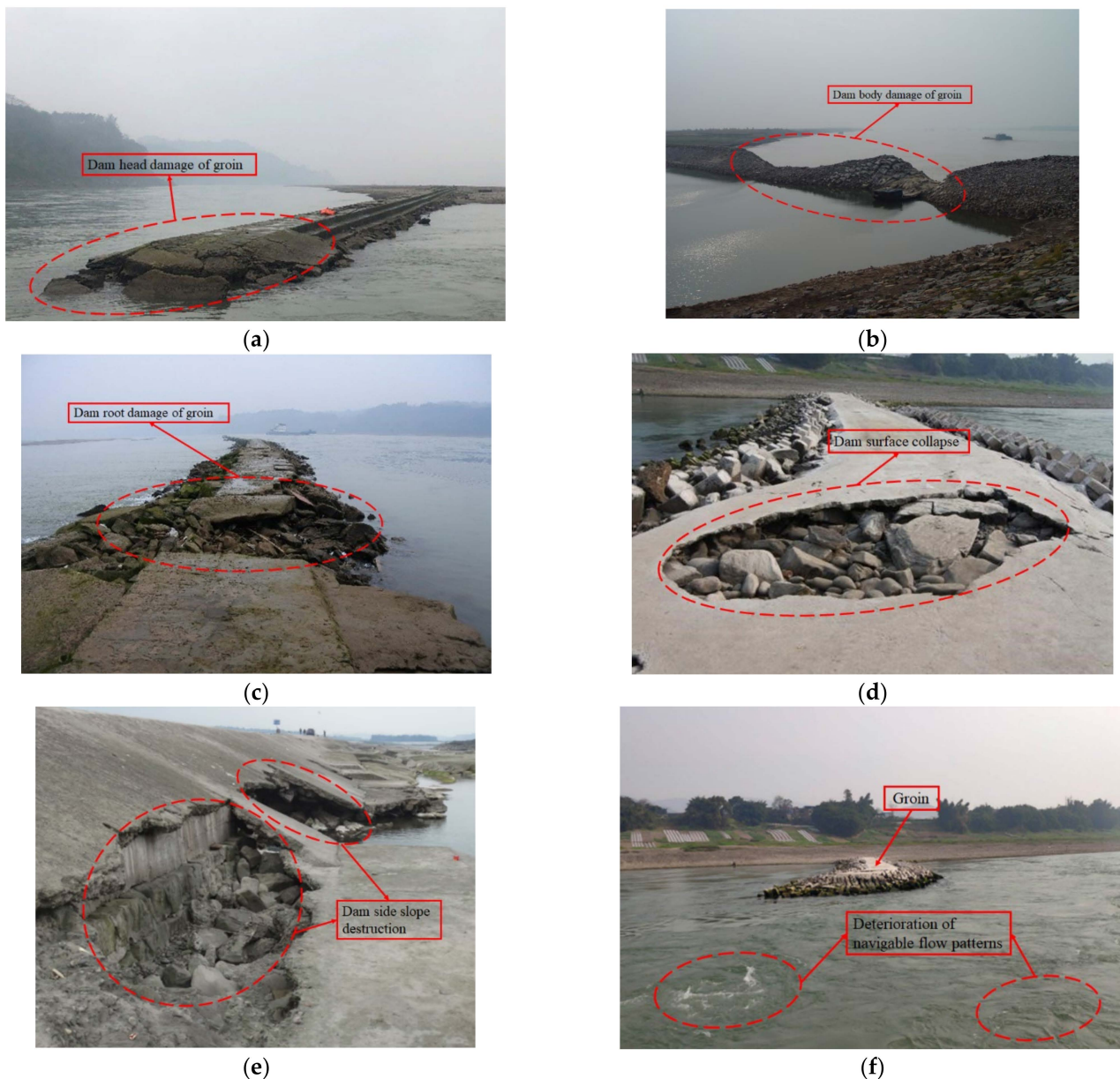


Figure 1. Common forms of groin structural damage and examples of its regulating functional degradation (the photos in (a,c–f) are from the daily shooting data of the Changjiang Waterway Bureau of China). (a) Dam head damage; (b) dam body damage; (c) dam root damage; (d) dam surface collapse; (e) dam side slope destruction; (f) deterioration of navigable flow patterns.

The degradation of the regulation function of spur dikes includes changes in the water flow conditions, the deterioration of the navigation flow regime, and an unsatisfactory channel scale caused by the evolution of scour and silt in the main channel. Figure 1f shows changes in the navigation flow due to groin damage.

Therefore, the service status of channel groins should be comprehensively evaluated from several aspects, such as the functional security of the spur dike, the appearance of deformation, the integrity of the dam body, and the structural stability.

2.2. Hierarchical Structure of the Evaluation Indicators and Site Description

According to the above analysis, an evaluation index system to determine the service status of groins in the waterway is established by decomposing the evaluation index into three levels: target, criterion, and elements. Waterway groins service status (WGSS) is

taken as the first-level total target, 4 s-level indicators constitute the criterion layer, and 16 third-level indicators constitute the element layer, as shown in Figure 2.

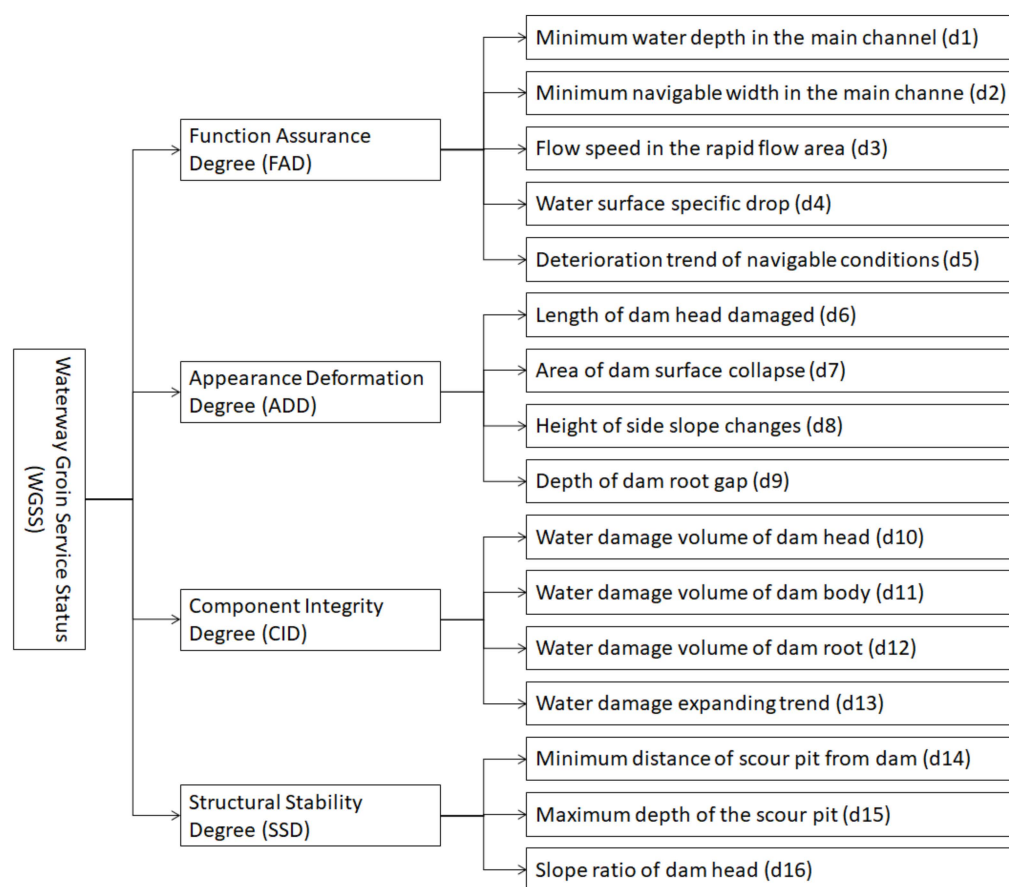


Figure 2. Evaluation index system to determine the service status of groins in a waterway.

The following paragraphs provide descriptions of the evaluation indicators at each level.

(1) Function Assurance Degree (FAD)

The FAD of groins includes five three-level indicators: minimum water depth in the main channel (d1), minimum navigable width in the main channel (d2), flow speed in the rapid flow area (d3), specific drop in the water surface (d4), and deterioration trend of navigable conditions (d5). The minimum depth of the main channel and the minimum width of the main channel reflect the adjustment effect of the groin on the scale of the channel; the flow velocity and water surface ratio drop in the rapid flow area reflect the improvement effect of the groin on the water flow condition of the channel; and the trend of the change in the navigation condition reflects the evolution effect of groin damage on the unfavorable navigation of the beach section.

(2) Appearance Deformation Degree (ADD)

The ADD of groins can visually reflect the damage state of the regulation structure and can help people to initially judge the stability state and development trends of each part of it using a total of four three-level indicators: length of dam head damaged (d6), area of dam surface collapse (d7), height of side slope changes (d8), and depth of dam root gap (d9).

(3) Component Integrity Degree (CID)

CID reflects the degree of structural retention of the dam after water damage and includes four three-level indicators: water damage volume of the dam head (d10), water damage volume of the dam body (d11), water damage volume of the dam root (d12), and

expanding trend of water damage (d13). During its service life, various parts of the groin may have different degrees of defects, divided across three component parts, namely the head, body, and root of the dam, and this damage can be quantified by the respective damage volume. In addition, if the degree of groin damage in the components develops rapidly over time, the stability of the overall structure will be endangered, so the dam body's trend of damage expansion also needs to be considered.

(4) Structural Stability Degree (SSD)

SSD reflects the degree of reliability of a groin structure to maintain stability. The most common groin instability is the sudden collapse of the dam head when the surrounding river bed is scoured to a certain degree due to the combined effects of steepening slope, its own gravity, and water flow [3,30]. In other words, the steeper the side slope, the closer the scour pit is to the head of the dam, and the deeper the pit is, the less favorable the stability of the groin structure will be. Therefore, considering both the head of the dam and the scour pit, three three-level indicators were selected to jointly measure the SSD: the minimum distance of the scour pit from the dam (d14), the maximum depth of the scour pit (d15), and the slope ratio of the dam head (d16). The scour pit-related parameters are shown in Figure 3.

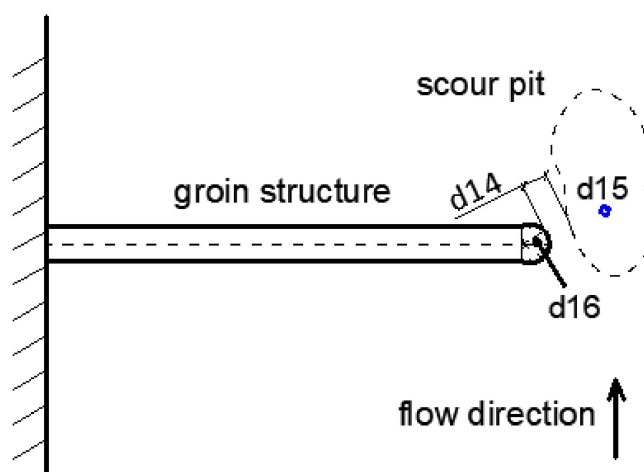


Figure 3. Parameters of scour pits near the groin head. The blue symbol indicates the location of the maximum depth of the scour pit (d15).

2.3. Quantitative and Grading Standard of Factor Layer Indicators

There are 16 impact indicators that can be used to determine the service status of groins, among which “the trend of deterioration of navigation conditions d5” and “the trend of water damage expansion d13” are qualitative indicators, and the measurement method compares the recent changes in navigable conditions and dam damage separately, analyzes the causes according to the actual situation, and judges the respective development trends, which refer to the actual practices carried out by the Yangtze River Waterway Management Department and Chinese industry standards [31,32]. The rest are quantifiable indicators and are quantified by the relative percentage of the reference value of the indicators.

Let the reference value of the index be s_{j0} and the sample measured value be s_{ij0} ; then, the quantitative score of the sample for indicator s_{ij} is

$$s_{ij} = \frac{s_{ij0}}{s_{j0}} \times 100\% \quad (1)$$

Among them, indicators d1~d4 take the local specification requirements of channel grade and channel conditions as reference values, and indicators d6~d12 and d14~d16 take the original design-standard values of the groin structure or the previous year's measurement values as reference values. In particular, d1, d2 and d15 are positive indicators,

and the larger the value, the better the result, while the rest of the indicators are negative indicators, and the smaller the value, the better the result.

The evaluation indexes of the service state of groins are both qualitative and quantitative, among which the quantitative indexes are divided into two types: positive and negative, and have the typical characteristics of multiple attributes. In order to eliminate the differences in the dimension between indicators and to facilitate the calculation, it is necessary to rate and assign uniform values to the indicator data. With reference to previous research results [10] and expert consultations, the evaluation indicators were divided into five levels, with values of 100, 80, 60, 40, and 20, respectively. For details, see Table 1.

Table 1. Classification and assignment standards of service status evaluation indexes of waterway spur dikes.

Evaluation Indicators	Score				
	100	80	60	40	20
Minimum water depth in the main channel d1 (%)	>97	90~97	80~90	70~80	<70
Minimum navigable width of the main channel d2 (%)	>97	90~97	80~90	70~80	<70
Flow rate in the rapid flow area d3 (%)	<3	3~10	10~20	20~30	>30
Water-surface ratio drop d4 (%)	<3	3~10	10~20	20~30	>30
Trend of deteriorating navigable conditions d5	No change	Slight change that does not affect the navigation	Moderate deterioration that has some impact on navigability	Significant deterioration that has a greater impact on navigation	Dramatic deterioration that makes the area unnavigable
Length of dam head damaged d6 (%)	<5	5~15	15~30	30~50	>50
Area of dam surface collapse d7 (%)	<5	5~10	10~20	20~40	>40
Height of side slope changes d8 (%)	<5	5~10	10~20	20~40	>40
Depth of dam root gap d9 (%)	<5	5~10	10~30	20~50	>50
Water damage volume of dam head d10 (%)	<5	5~10	10~20	20~30	>30
Water damage volume of dam body d11 (%)	<5	5~10	10~20	20~30	>30
Water damage volume of dam root d12 (%)	<5	5~10	10~20	20~30	>30
Water damage expanding trend d13	No change	Small changes that do not affect structural stability	Localized changes that may affect structural stability	Significant changes that have a large impact on structural stability	Rapid changes leading to structural instability
Maximum depth of scour pit d14 (%)	<10	10~20	20~30	30~40	>40
Minimum distance of scour pit from dam d15 (%)	>40	30~40	20~30	10~20	<10
Slope ratio of dam head d16 (%)	<5	5~10	10~20	20~30	>30

3. AHP-Improved CRITIC Combination Weighting Evaluation Model

Single-weight assignment methods are often deficient, while combined weights can both compensate for the deficiencies of single methods and integrate their respective advantages, thus improving the accuracy of weight evaluation results. Therefore, this paper proposes an AHP-improved CRITIC method-combined weighting evaluation model: subjective and objective weights are calculated simultaneously for the groin evaluation indexes

and are optimally combined using the least squares method. Finally, the comprehensive score of the index system is calculated by linear weighting.

3.1. Subjective Weight Calculation Method

The subjective weights were calculated using the analytic hierarchy process method (hereinafter referred to as AHP). AHP is a commonly used subjective assignment method and is very suitable for multi-objective decision analysis combined with qualitative and quantitative analyses [18]. The algorithm principle of AHP is shown in Figure 4.

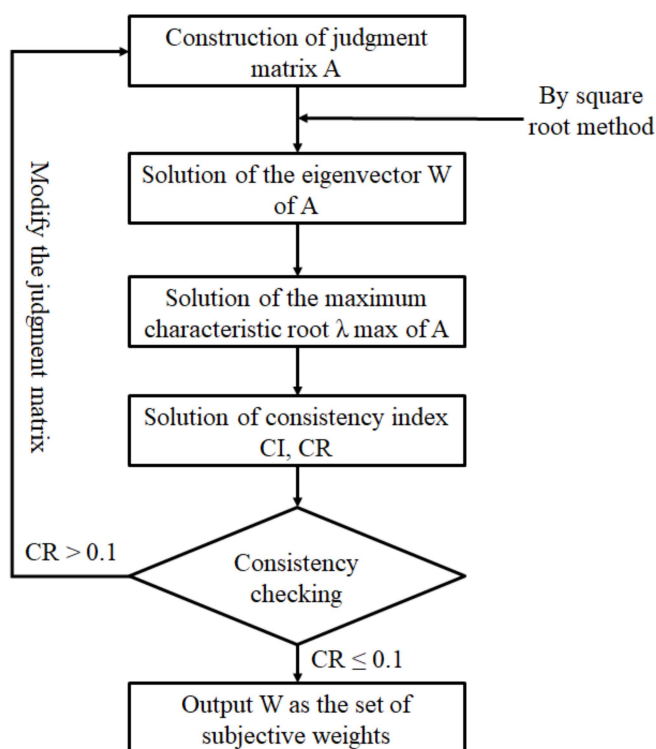


Figure 4. The principle of AHP weighting algorithm.

The specific calculation steps are as follows:

(1) Construction of judgment matrix

According to scales 1~5 shown in Table 2, the judgment comparison of the importance among the indicators is carried out with reference to expert opinions, and the judgment results are expressed by these values to construct judgment matrix A.

Table 2. Judgment matrix assignment basis.

Scale Value	Meaning
1	Equally important
3	Slightly more important
5	Obviously important
2, 4	Level of importance between the above three levels

(2) Consistency check

The maximum eigenvalue of judgment matrix A is solved according to the square root method, and the consistency ratio CR value is calculated according to Equations (2) and (3).

If $CR < 0.1$, then the judgment matrix is considered to pass the consistency test; if not, the judgment matrix is modified until $CR < 0.1$.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

where λ_{max} is the maximum eigenvalue of the judgment matrix; n is the order of the judgment matrix; CI is the consistency index; and RI is the random consistency index.

(3) Solving for weights

When the judgment matrix passes the consistency test, the weight w_j ($j = 1, 2, \dots, n$) is obtained using its normalized eigenvector as the weight vector W .

3.2. Objective Weight Calculation Method

The objective weights were calculated using the improved CRITIC method. The CRITIC method (Criteria Importance Through Intercriteria Correlation) is a weight calculation method proposed by D. Diakoulaki et al. [33]. The basic idea is to assign weights based on the amount of information and correlation contained in the indicator data. When the degree of variation among indicators can reflect the amount of information carried and the size of the conflict among indicators can reflect the correlation, they are measured by standard deviation and correlation coefficient, respectively [28]. In order to reduce the influence of errors introduced by different magnitudes and orders of magnitude, later on the basis of the CRITIC method, the standard deviation was replaced by the coefficient of variation and called the improved CRITIC method [29]. Its calculation process is shown in Figure 5.

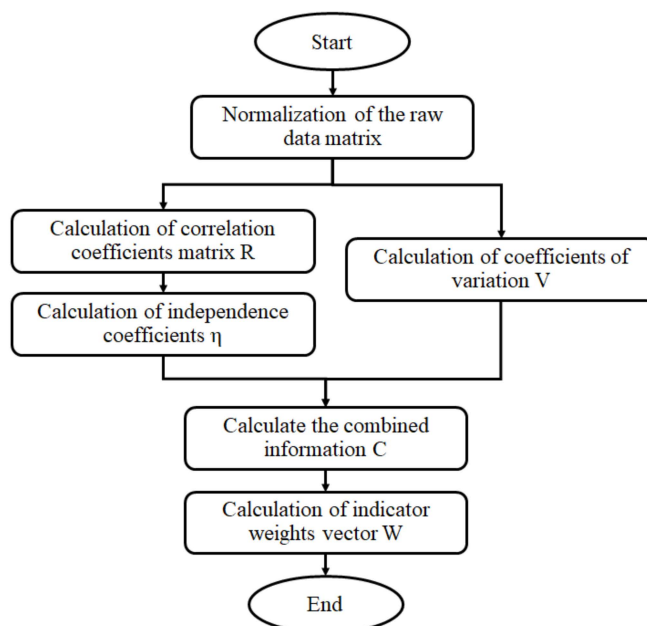


Figure 5. The principle of the weighting algorithm of the improved CRITIC method.

Assuming that there is a system with m objects to be evaluated and n evaluation indicators and that the j indicator of the i object takes the value x_{ij} to form the value matrix of the original evaluation indicator $X = (x_{ij})_{m \times n}$, the steps to apply the improved CRITIC method to evaluate the weights of this indicator system are as follows:

(1) Normalization of the raw data matrix

The Z-score method was used to standardize the values of each indicator in the matrix X . The mean value $\bar{x}_j$ and standard deviation $\bar{s}_j$ were calculated for the first indicator

j , and the standardized values were standardized to produce the standardized matrix $X^* = (x_{ij}^*)_{m \times n}$.

$$\bar{x}_j = \frac{1}{m} \sum_{i=1}^m x_{ij} \quad (j = 1, 2, \dots, n) \quad (4)$$

$$\bar{S}_j = \sqrt{\frac{1}{m} \sum_{i=1}^m (x_{ij} - \bar{x}_j)^2} \quad (j = 1, 2, \dots, n) \quad (5)$$

$$x_{ij}^* = \frac{x_{ij} - \bar{x}_j}{\bar{S}_j} \quad (i = 1, 2, \dots, m; j = 1, 2, \dots, n) \quad (6)$$

- (2) Calculation of coefficients of variation, correlation coefficients, and independence coefficients of indicators

The coefficient of variation of the j indicator is

$$V_j = \frac{S_j}{\bar{x}_j} \quad (j = 1, 2, \dots, n) \quad (7)$$

and the correlation coefficient matrix $R = (r_{kl})_{n \times n}$ is found based on the normalization matrix X^* :

$$r_{kl} = \frac{\sum_{i=1}^n (x_{ik}^* - \bar{x}_k^*)(x_{il}^* - \bar{x}_l^*)}{\sqrt{\sum_{i=1}^n (x_{ik}^* - \bar{x}_k^*)^2} \sqrt{\sum_{i=1}^n (x_{il}^* - \bar{x}_l^*)^2}} \quad (r_{kl} = r_{lk}; k = 1, 2, \dots, n; l = 1, 2, \dots, n) \quad (8)$$

where r_{kl} is the correlation coefficient between the k and l indicators, and $\bar{x}_k^*$ and $\bar{x}_l^*$ are the average of the standardized values of the X^* , k , and l evaluation indicators in the standardization matrix.

This allows the quantitative coefficient of the degree of independence of the indicators to be calculated. The independence coefficient of the j indicator is

$$\eta_j = \sum_{k=1}^n (1 - r_{kj}) \quad (j = 1, 2, \dots, n) \quad (9)$$

- (3) Calculation of indicator weights

The calculation combining the indicator information for the j indicator is

$$C_j = V_j \eta_j \quad (j = 1, 2, \dots, n) \quad (10)$$

This results in the weighting of the first j indicator ω_j being

$$\omega_j = \frac{C_j}{\sum_{j=1}^n C_j} \quad (j = 1, 2, \dots, n) \quad (11)$$

3.3. Weight Assignment of Indicators of Element Layer to the Target Layer

The two methods described above can be used to calculate the weight assignments for any adjacent layer in the indicator hierarchy. To determine the weight assignments of individual indicators to the total target layer, the weight assignments of each layer need to be calculated layer by layer and then aggregated.

If there are n evaluation indicators in the factor layer and l evaluation indicators in the criterion layer, let w_j be the weight contribution of the j th indicator in the element layer to the overall objective. $v_{k,j}$ is the weight contribution of the j th indicator in the element layer

to the k th indicator in the criterion layer. If v_k is the weight contribution of the k th indicator in the criterion layer to the total target, then the weight distribution of the single indicator to the total target layer is

$$w_j = v_{k,j} \times v_k, j = 1, 2, \dots, n; k = 1, 2, \dots, l \quad (12)$$

The set of subjective weights calculated by the AHP method is expressed as the vector $W^{(1)} = (w_j^{(1)})_{1 \times n}$.

Additionally, the set of objective weights calculated by the modified CRITIC method is expressed as the vector $W^{(2)} = (w_j^{(2)})_{1 \times n}$.

3.4. Combined Weight Optimization Model

The AHP method mainly relies on expert experience, while the improved CRITIC method relies entirely on actual measurement data, and the weights calculated by both methods are relatively one-sided. Therefore, the two methods are fused so that the computed combined weights can reflect both expert experience and objective data information.

Typical methods for combining algorithms include power-average synthesis and optimization methods [27], and in this paper, the combined-weight optimization model is established using the least squares method and is solved using the Lagrange multiplier method.

The standardized numerical matrix of the evaluation indicators is $X^* = (x_{ij}^*)_{m \times n}$. If the index weight is w_j ($j = 1, 2, \dots, m$), then by using the expectation benefit method [23], the evaluation value of point f_i is:

$$f_i = \sum_{j=1}^n w_j x_{ij}^*, j = 1, 2, \dots, n; i = 1, 2, \dots, m$$

The weights of each indicator obtained from the AHP method and the improved CRITIC method are $w_j^{(1)}$, and $w_j^{(2)}$. We should choose the weight vector w_j ($j = 1, 2, \dots, m$), and for the overall value evaluation of overall evaluation points, the smaller the better, and it is according to this that the following least squares optimization evaluation model is established:

$$\begin{cases} \min \sum_{i=1}^m \sum_{j=1}^n \left[(w_j - w_j^{(1)})^2 x_{ij}^{*2} + (w_j - w_j^{(2)})^2 x_{ij}^{*2} \right] \\ \text{s.t.} \begin{cases} \sum_{j=1}^n w_j = 1 \\ w_j \geq 0, j = 1, 2, \dots, n \end{cases} \end{cases} \quad (13)$$

To solve the above model as a Lagrange function:

$$L = \sum_{i=1}^m \sum_{j=1}^n \left[(w_j - w_j^{(1)})^2 x_{ij}^{*2} + (w_j - w_j^{(2)})^2 x_{ij}^{*2} \right] + \lambda \left(\sum_{j=1}^n w_j - 1 \right) \quad (14)$$

Let $\frac{\partial L}{\partial w_j} = 0$, and solve using the equation $\sum_{j=1}^n w_j - 1 = 0$ so that the weight vector of the indexes is obtained as $W = (w_1, w_2, \dots, w_n)$.

3.5. Comprehensive Score Calculation Method

The linear weighting method is often applied for the comprehensive calculation of index systems [10,27]. The service status of a spur dike is reflected by the comprehensive index Z . The linear-weighted comprehensive evaluation method is used to calculate the score of Z . The specific calculation formula is

$$Z = \sum_j w_j r_j, j = 1, 2, \dots, n \quad (15)$$

where r_j is the score of the j th indicator and w_j is the combined weight of indicator j on the total target layer.

On the one hand, the calculated comprehensive index Z , can help people to make simple and intuitive judgments on the service status of a spur dike as a whole, and on the other hand, it can be used for comparisons with the actual evaluation level to verify the reliability and accuracy of the model. In addition to this, actual evaluation work also needs to analyze each spur dike service status index and conduct a comprehensive evaluation and make decisions according to the actual situation.

4. Case Study

In order to verify the reliability and applicability of the model, the model was applied to the upper Yangtze River waterway for a comprehensive evaluation of the service status of one of the groins. The original data used for the objective weight calculation were taken from 13 additional groin samples, and Figure 6 shows the distribution of the validation spur dikes and all of the objective samples in the upper Yangtze River channel.

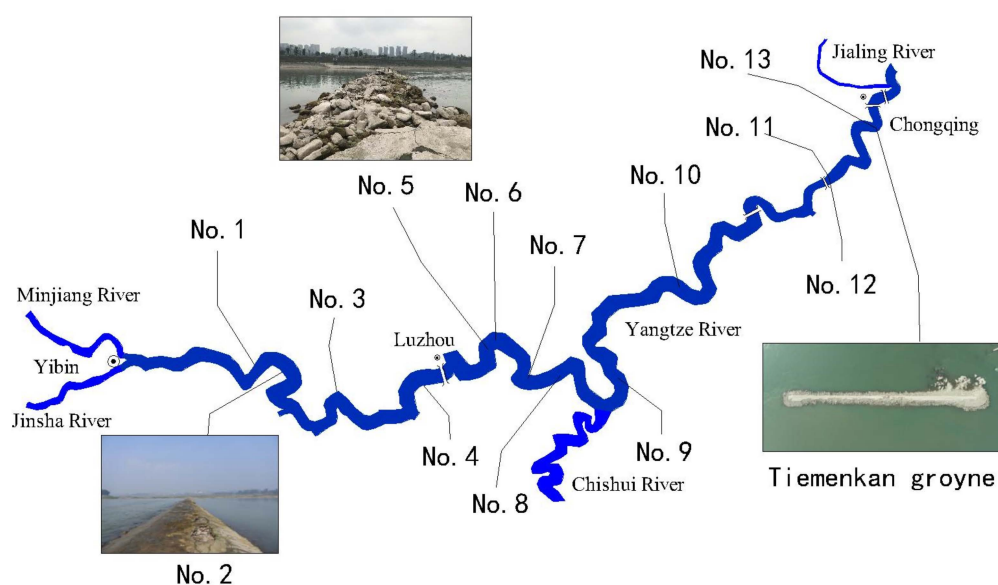


Figure 6. Distribution of the validation spur dikes and all of the objective samples in the upper Yangtze River channel. The figure shows the locations and numbered names of all of the groin samples selected in the upper Yangtze River for this paper, including 13 groin samples in the objective sample set and 1 validation sample (Tiehmenkan groin). Among them, photos of samples No. 2, No. 5, and the Tiehmenkan groin are shown in the figure (the photos of the groins in the picture are from the daily shooting data of the Changjiang Waterway Bureau of China).

4.1. Project Background

The upper reaches of the Yangtze River range from Yichang, Hubei Province, to Yibin, Sichuan Province, China. This river has a total length of about 1030 km and is a typical mountainous river. The river bed in this section is relatively steep and narrow, and the river level and flow vary greatly, so the navigation conditions are complex and varied. In order to improve the water flow conditions and to enhance the navigability scale, six systematic long-river section management projects have been carried out so far, and a total of more than 50 beach hazards have been rectified. The main means of improvement used in these projects is the construction of various types of groin buildings; however, due to the influence of various complex factors, the destruction of channel improvement buildings in the upper Yangtze River is also particularly common [3].

The damage of spur dikes and the dramatic evolution of the surrounding riverbed in the upper reaches of the Yangtze River often occur during flood season, and during the dry period, the state of spur dikes is more stable due to the lower flow and smoother water flow. Considering the convenience of index data collection and construction, the waterway

management department conducts field observations of the improvement buildings and performs construction maintenance at the end of the previous year and the beginning of the next year, which is when the Yangtze River enters the dry water period, and these observations and maintenance are carried out every year according to the relevant codes and standards [31]. The data used in this paper are mainly daily maintenance information for the upstream waterway obtained by the Changjiang Waterway Bureau of China.

The Tiemenkan groin, which is located at a channel mileage of 676.4 km, was selected as the validation sample. This groin is located in a section of the river with a bridge and in a location in which there are reefs in the river. This groin has been subject to continuous impact and scouring by the current for a long time. The actual measurement data of the Tiemenkan dike for 2021 showed that half of the backwater slope of the top surface of the dam showed obvious collapse damage, and the accumulated damage length was more than 150 m, accounting for more than 80% of the total length of the dam; the side slopes were generally intact, and only a small number of boulders were lost locally; the backwater slope of the top side of the dam was mostly uneven, and there was even obvious local collapse damage, and the elevation was lowered by more than 1.0m; the possibility of further deterioration of the dam body is very high, and the scour pits are obviously developed. The flow in the upper section of the beach is smooth, and the direction is basically the same as that of the deep flood line, while the local flow lines in the lower section being obviously crossed; the maximum flow velocity is about 2.2 m/s, and the minimum flow velocity is below 1.0 m/s; the channel siltation is large, and the navigational environment is complicated but does not affect navigation.

In addition, a number of samples of actual original data are needed to calculate the objective weights of the service status indicators of groins. Measured data of 13 representative groins in the upper reaches of the Yangtze River were collected as an objective sample set in 2021, and the numbering and location distribution of the samples are shown in Figure 6. The basic information of the samples is shown in Table 3.

Table 3. Basic information of objective sample sets (several of them) in 2021.

Sample No.	Building Name	The Waterway Mileage Where the Groin Is Located (km)	Qualitative Description of the Technical Conditions of Groin		
			Waterway Conditions	Dam Conditions	Scouring Situation near the Dam Head
1	Xiaojibei #1 submerged groin	1003.6	Tight channel scale, smooth flow pattern, high flow velocity	Dam root elevation reduction	Slope ratio slightly steeper
2	Youzhaqi upstream groin	994.0	Tight channel scale and local flow disturbance	Dam surface stripping damage, side slope steepening	Scouring pit development
3	Fengboqi Daodingshun groin	959.3	Tight channel scale, smooth flow pattern, high flow velocity	Inflection point overhang damage, side slope steepening	The slope is relatively steep
13	Cubingqi groin	676.2	Large channel siltation, complex navigable environment	Dam face stripping damage, the top of the dam is vulnerable to continuous damage	Stable

4.2. Evaluation Process

(1) Organize raw data and score the indicators

The raw information of each groin including the objective sample set was collated. According to Equation (1), standard quantification was performed on the actual measured indicator data. Additionally, each indicator was rated according to Table 1 to obtain the indicator rating scores for the set, which are included in Table 4.

Table 4. Index scores of objective samples.

Sample No.	Indicator Code															
	d1	d2	d3	d4	d5	d6	d7	d8	d9	d10	d11	d12	d13	d14	d15	d16
1	60	60	60	60	80	100	80	80	40	100	80	40	80	100	100	60
2	100	100	80	60	80	40	80	40	80	40	80	80	60	20	20	20
3	80	40	80	80	80	80	40	40	80	60	40	80	60	40	40	40
4	100	80	60	80	80	80	80	60	100	60	60	100	60	40	60	60
5	80	80	100	100	80	80	40	80	100	80	60	100	60	60	60	60
6	100	100	40	60	80	80	80	80	60	80	80	40	60	60	60	60
7	100	100	80	80	80	80	80	40	80	60	60	60	60	80	80	60
8	80	40	80	80	60	80	60	60	80	80	60	80	60	80	80	80
9	100	100	60	60	80	20	40	40	40	20	40	40	40	60	60	40
10	100	100	80	80	80	60	60	80	100	60	60	60	80	60	80	60
11	100	60	40	60	80	100	60	80	80	100	60	60	80	80	60	80
12	100	60	40	60	80	60	80	60	100	60	80	100	80	60	80	80
13	100	80	80	80	80	100	20	60	80	100	40	80	60	80	80	80

(2) Calculate the subjective weights of the service status indicators

Expert scoring based on historical experience was used to establish a judgment matrix for the dependent indicators between adjacent layer.

The first-level judgment matrix is as follows:

$$A_B = \begin{bmatrix} 1 & 3 & 2 & 1 \\ 1/3 & 1 & 1/2 & 1/2 \\ 1/2 & 2 & 1 & 1/2 \\ 1 & 2 & 2 & 1 \end{bmatrix}$$

The secondary judgment matrices are as follows:

$$A_{b1} = \begin{bmatrix} 1 & 2 & 3 & 4 & 5 \\ 1/2 & 1 & 2 & 3 & 4 \\ 1/3 & 1/2 & 1 & 2 & 3 \\ 1/4 & 1/3 & 1/2 & 1 & 2 \\ 1/5 & 1/4 & 1/3 & 1/2 & 1 \end{bmatrix}; A_{b2} = \begin{bmatrix} 1 & 6 & 4 & 2 \\ 1/6 & 1 & 1/3 & 1/4 \\ & 1 & 1/3 & \\ & 1/4 & 1 & \\ & & & 1 \end{bmatrix}$$

$$A_{b3} = \begin{bmatrix} 1 & 1/2 & 2 & 3 \\ 2 & 1 & 2 & 4 \\ & 1 & 2 & \\ 1/2 & 1/2 & 1 & \end{bmatrix}; A_{b4} = \begin{bmatrix} 1 & 2 & 1/2 \\ 1/2 & 1 & 1/3 \\ 2 & 3 & 1 \end{bmatrix};$$

Calculate the weights of each layer of the index system according to the calculation steps for the AHP method and then calculate the weight of the indicators of the element layer to the target layer using Equation (12) to determine the subjective weight vector: $W^{(1)} = (0.15, 0.09, 0.06, 0.03, 0.02, 0.06, 0.01, 0.02, 0.04, 0.06, 0.08, 0.04, 0.02, 0.10, 0.05, 0.18)$.

(3) Calculate the objective weights of the service status indicators

Obtain the original data matrix corresponding to the index system from Table 3, calculate the weights of each layer according to Equations (4)–(11), calculate the weights of the indicators of element layer to the target layer by Equation (12), and obtain the objective weight vector: $W^{(2)} = (0.04, 0.07, 0.08, 0.05, 0.02, 0.04, 0.06, 0.04, 0.04, 0.06, 0.04, 0.07, 0.02, 0.12, 0.11, 0.14)$.

(4) Calculate the combination weights of the service status indicators

The calculated subjective weights, objective weights, and objective sample data from Table 3 are substituted into Equation (14) and solved according to the Lagrange multiplier method to obtain the combined weight vector: $W = (0.09, 0.08, 0.07, 0.04, 0.02, 0.05, 0.03, 0.03, 0.04, 0.06, 0.06, 0.05, 0.02, 0.11, 0.08, 0.16)$.

(5) Calculate the comprehensive score of the service status of the groin

Based on the actual measurement data of the Tiemenkan groin, its service status indicators are rated and assigned by Equation (1) and Table 1, and the indicator scores are expressed in vector form as $R = [r_j]_{1 \times 16} = [100, 80, 80, 80, 80, 80, 40, 20, 40, 40, 40, 20, 40, 60, 60, 60, 60]$.

The combined weights and scores of the calculated indicators are substituted into Equation (15), and the composite score of the service status of the spur dike is obtained by calculating $Z = 59.0$.

4.3. Evaluation Results and Discussion

4.3.1. Evaluation Results

The overall evaluation score of the WGSS of the Tiemenkan groin is 59, which is on the low side. The FAD of the groin is basically intact, but the ADD and CID are severely damaged, and the SSD is poor. The evaluation results showed that it should be repaired in a timely manner to ensure the safety of the structure and improve the navigation of the spur dike.

In fact, in May 2021, the local waterway management department also evaluated the spur dike as “The dam surface collapse damage, the top of the dam is damaged, and the stability of the dam body is reduced, in addition to the groin may lead to the deterioration of the navigable conditions of this beach section after the increased damage, thus it is recommended that the Tiemenkan groin be repaired this year”. Figure 7 shows an on-site photograph of the Tiemenkan groin. This proves that the evaluation results of the AHP-improved CRITIC-combined assignment optimization model are consistent with the actual situation, indicating that the reliability and applicability of the model are good and that the service status of groins in waterways can be quantified and comprehensively evaluated using the method proposed in this paper.



Figure 7. Image from the 2021 site inspection of the Tiemenkan, which showed that most of the dam surface has been half-stripped (the photo is from the daily shooting data of the Changjiang Waterway Bureau of China).

4.3.2. Uncertainty Analysis of Qualitative Indicators

In order to clarify the degree of influence of the measurement method of the two qualitative indicators d5 and d13 in the evaluation system on the WGSS, the amount of data information carried by the 16 indicators in the sample set was analyzed. According to the calculations of standard deviations of the samples for each piece of indicator data

in Table 4, it can be seen that the values of the 16 indicators are distributed between 5.55 and 23.97, among which the standard deviation of d5 is 5.55, which is 0.23 times higher than the maximum value of 23.97, and d13 is 11.98, which is 0.5 times higher than the maximum value; in addition, the comprehensive weight coefficients of both d5 and d13 were calculated as 0.02 in Section 4.2, showing that the groin state has a certain sensitivity to changes in the two indicators. This indicates that the results of the two qualitative indicators have a more obvious influence on the WGSS and further proves that the measurement is feasible and applicable.

4.3.3. Comparison with Single-Weight Assignment Results

Comparing the combined weights calculated by the optimization model with the subjective weights calculated by the AHP method and the objective weights calculated by the improved CRITIC method, it was found that the differences between the different sets of weight assignments were large. Among them, the subjective weight of the index set showed the largest degree of variation, the objective weight had a small degree of variation, and the combined weight was between the two, as shown in Figure 8.

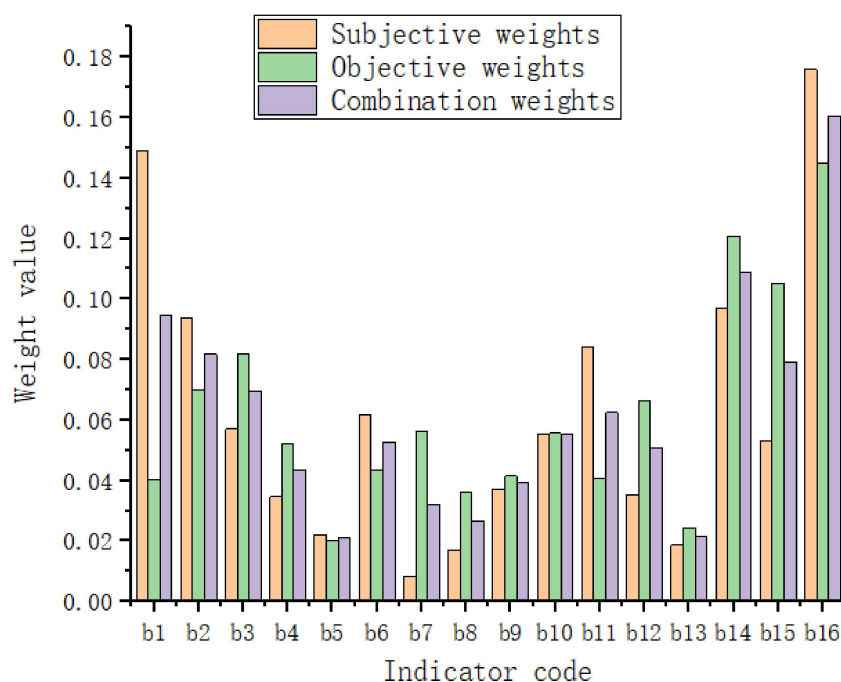


Figure 8. Comparison of the results of different indicator weight assignments.

The weights obtained by the AHP method mainly rely on expert experience, which has certain subjective limitations. The weights obtained by the improved CRITIC method also have objective limitations: it cannot make suitable subjective bias adjustments according to the actual situation and cannot completely replace expert experience, so the information contained in both subjective and objective weights is one-sided and insufficient. The weight assignment results obtained by fusing the above two assignment methods are obviously more reasonable and credible, as they take into account expert experience and have some objective basis.

4.3.4. Comparison of Evaluation Results Using Traditional Methods

To evaluate the service status of groins and to make maintenance decisions, one common approach to waterway management was to classify waterway improvement buildings into four categories according to their structural and functional conditions and to provide different maintenance recommendations based on those categories. The first three columns of Table 3 provide the classification criteria for the technical conditions of inland

waterway improvement buildings in China. For comparison with the locally measured results, the composite Z-score calculated using the new model proposed in this paper was divided equally according to the four categories, and column 4 of Table 5 shows the score intervals corresponding to Z.

Table 5. Evaluation criteria for the technical conditions of inland waterway improvement buildings in China and the corresponding Z-score interval.

Category Classification	Technical Condition of the Waterway Improvement Buildings	Maintenance Recommendations	Z-Value Range
I	Good technical condition and normal function	No need for maintenance	(80, 100)
II	The building has a small amount of deformation, but it does not affect the building stability and remediation function	Suspended maintenance	(60, 80)
III	Building damage is more obvious and can still play a remediation function, but timely repairs are needed	Maintenance	(40, 60)
IV	The building is seriously damaged or has obvious defects and has lost or will lose remediation function	Maintenance	(20, 40)

Note: Because $x_{ij} \geq 20$ in Table 1, the distribution interval of the Z-scores is as in (20, 100).

The WGSS of the previous 14 groin samples were synthesized using the traditional AHP method and the new model to verify the calculation accuracy of the two methods, and the results are shown in Figure 9. The 14 groin samples include the Tiehmenkan groin and the 13 other real groins that make up the objective sample set, and all of them were tested using the same validation process. The difference is that the latter 13 spur dikes are the source of the data used for calculating the objective weights of the new model, while the Tiehmenkan spur dike is a location that is not included in the objective sample set, so its validation results can reflect the applicability of the new model.

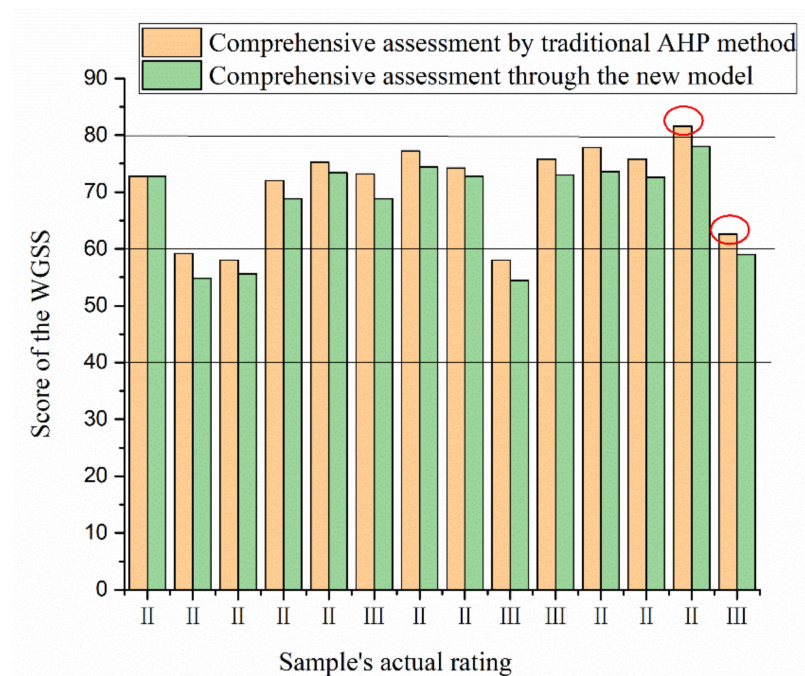


Figure 9. Comparison of the results of the comprehensive assessment of WGSS using different methods. The horizontal axis is the actual evaluation category of the selected groins determined by the local waterway management department, and the horizontal line in the figure represents the boundaries of the corresponding scoring interval. The red circles mark calculated scores that are outside the actual rating range.

As seen in Figure 9, compared to the actual ratings, the combined calculation results determined using the traditional AHP weight assignment method have two discrepancies (circled in red), while the calculation results obtained using the new model proposed in this paper are completely consistent. Obviously, the comprehensive evaluation results obtained using the combined-weight assignment method are more accurate than those obtained using the traditional evaluation method, and it further shows that the combined-weight assignment method is more reasonable and credible than the single-weight assignment method.

The index weights calculated by the AHP method can only reflect expert experience, and these calculation results mainly rely on the accuracy of subjective judgment, which cannot accurately reflect the effective information carried by the index itself, so the results calculated using this traditional method will likely show errors when compared to the actual situation. The new method proposed in this paper tries to optimize the calculation of indicator weights, and through combination with the improved CRITIC method, it can take into account both subjective and objective information, allowing the method to make more reasonable weight calculations despite the increased number of calculation steps. The comparison shows that the new method is more accurate than the traditional method, more consistent in actual situations, and obtains more satisfactory results.

The improved CRITIC method takes into account both the indicator information and the correlation between indicators and achieves significant superiority, making it ideal for objective weight calculation applications. It is suggested that in the future, when the service status of groins is comprehensively evaluated, objective weights should be added on the basis of subjective assignment and that the AHP-improved CRITIC-combined assignment optimization model should be used for calculation.

The above results show that the comprehensive evaluation method to determine groin service status based on combining assignment weights proposed in this paper is more scientific and accurate than the traditional method and that it can provide an accurate quantification and comprehensive evaluation of the service status of groins in waterways as well as a scientific basis for maintenance decisions to maintain the sustainability of groin function.

5. Conclusions

At present, waterway infrastructure evaluation methods are still relatively traditional, and most of them only work at the qualitative level, relying entirely on manual discrimination, meaning that they can only obtain relatively rough results and do not facilitate unified coordination and management. The application of scientific and accurate evaluation methods for waterway infrastructure management will probably become a demand and development trend in the future as the Chinese waterway management authorities continue to carry out the construction and management of intelligent waterways. The work in this paper is a useful exploration of the construction of intelligent waterways, and the proposed method helps to improve the construction and management of waterways, which has some practical significance and value.

This paper analyzes the connotation and influencing factors of the service status of channel groins, constructs an evaluation index system with the following hierarchical structure: target, criteria, and factor, and proposes a comprehensive evaluation model based on the combination of AHP-improved CRITIC weighting by integrating subjective and objective weights using the least squares principle. The model was also validated and analyzed by selecting 1 typical spur dike and 13 representative groins in the upper Yangtze River channel as the validation sample and the original data set, respectively. The main conclusions are as follows:

- (1) In view of the influencing factors and functional characteristics of the groin damage in the waterway, a service condition evaluation index system was constructed with FAD, ADD, CID, and SSD as the judging criteria and 16 indicators as the basic elements. At the same time, the measurement methods of the element indexes were provided, and the criteria for rating and assigning values were formulated according to their

multi-attribute characteristics. Through a practical test, the evaluation index system showed good applicability to channel groin evaluations and can measure and rate the indexes conveniently and efficiently.

- (2) A combined assignment optimization model based on the least squares principle of AHP and the improved CRITIC method was established and solved using the Lagrange multiplier method. Through calculation and comparison, the combined weights of the evaluation indexes reflect both subjective and objective information regarding the service status of groins that is more reasonable and credible than the information provided by the single assignment method. The combined weighting optimization model combines the respective advantages of the subjective and objective weighting methods and makes up for the shortcomings of the single weighting method.
- (3) Through example verification, the comprehensive evaluation results of the service status of the validation sample obtained by the new model established in this paper are consistent with the actual situation, and the reliability and applicability of the model are good; through the comprehensive calculation of the service status index scores of 14 groins using subjective weights and combined weights, we found that the new model is more accurate than the traditional evaluation method.
- (4) The proposed AHP-improved CRITIC-combined weighting optimization model developed based on the comprehensive evaluation method to determine the service status of waterway groins has obvious advantages and can accurately quantify and comprehensively evaluate the service status and provide a scientific basis for decision-making to maintain the sustainability of the dam's function.
- (5) However, the authors recognize that the work in this paper has some limitations and presents possibilities for future research. First, despite the inclusion of objective weights, the evaluation method proposed in this paper still has some subjectivity, such as in the formulation of the index system, in the collection and scoring of some of the index information, and in the determination of subjective weights, which may lead to the estimation accuracy being distorted; in addition, the proposed evaluation index system includes 16 indicators, which is a large number, and considering the practical application of the evaluation method, for the current service status assessment, collecting basic information/data takes a lot of time and is expensive, and it is necessary to think about how to simplify the task by improving the efficiency. These problems are often unavoidable in the research and implementation of comprehensive evaluation methods; therefore, there is a need for continued optimization and further research on evaluation methods.
- (6) In practice, the characteristics of remediation buildings differ in different river basins and river sections, therefore, it may make significant errors if the results of this paper are completely replicated when the model is applied in different river sections. As a result, when engineers and waterway administration authorities use this model, it is necessary to note that the evaluation index set should be adjusted according to the actual situation. The weight coefficients must also be recalculated if the river segment environment differs from that of the upper Yangtze River.

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