Study on the Evaluation Model of Earth-Rock Dam Failure Consequences Based on Combined Weighting and Extensible Cloud Model

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Abstract. The reservoir dam disaster is characterized by its suddenness, and the consequences of dam failure are unbearable for people. In order to accurately understand and determine the severity of the consequences of reservoir dam failure, and to ensure the safety and interests of downstream public, this paper comprehensively evaluates the consequences of small and medium-sized earth-rock dams' failure based on the current research status. In this paper, the combination weighting method is used to calculate subjective and objective weights, which not only compensates for the shortcomings of subjective and objective weights but also considers the advantages of both. To ensure that the information of subjective and objective weights is not lost, the minimum information discrimination principle is adopted to determine the comprehensive weight. By combining the advantages of uncertainty inference of the cloud model and the qualitative and quantitative analysis of extensible matter-element theory, a comprehensive evaluation model of extensible cloud dam failure consequences based on combined weighting is constructed. The effectiveness and applicability of the model are verified by using small and medium-sized reservoirs' data to evaluate the severity of reservoir dam failure consequences.

Keywords: earth-rock dam; Combined weighting; Extended cloud model; Consequence of dam failure.

1 Introduction

China has nearly 100,000 reservoir dams, of which earth-rock dams account for more than 95% of the total number of reservoir dams in China, and most of them are small and medium-sized reservoirs, which were built in the 1950s to 1970s [1-2], and there are certain risks in terms of safe operation. Earth-rock dam failure has the characteristics of great loss of people's lives and property, bad impact on ecological environment, and will also restrict the development of the country and society, so it is of great significance to conduct a comprehensive evaluation of the consequences of dam failure.

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In recent years, a large number of scholars have been devoted to the damage assessment of dam failure, which is mainly conducted according to the characteristics of dam body, geographical location and population distribution. Assaf et al. [3] estimated the life loss of dam break based on the simulation technology of dam break model. McClelland of the US Bureau of Reclamation and Dekay of the University of Colorado [4] estimated life loss based on the population at risk existing in the dam break area, and established an empirical estimation formula describing the nonlinear relationship between the population at risk and life loss. Daniell J E[5] studied the assessment framework of indirect economic losses of natural disasters; Barlettani et al. [6] proposed to define the degree of environmental impact by measuring the vitality of environmental loss. Domestic scholars built a loss model suitable for the characteristics of domestic reservoirs on the basis of foreign studies. Li Lei, Peng Xuehui et al. [7] used Graham method to evaluate the life loss of dam break in Shahe reservoir of Chuzhou City, Anhui Province. Wang Zhijun et al. [8] built a GIS-based assessment model of dam break life loss. Wang Zhijun et al. [9] introduced the matter-element evaluation method into the division of the flood area of dam break, so as to build the direct economic loss evaluation model of the flood area of dam break. He Xiaoyan et al. [10] built an evaluation index system to complete the social and environmental fuzzy evaluation of dam break based on different modes of dam break occurrence and the downstream environment of dam break reservoir and other data.

At present, the multi-index evaluation model used to construct dam break loss assessment mainly adopts the analytic hierarchy process (AHP) and fuzzy theory methods, divides the schemes, criteria and objectives hierarchically, and compares multiple factors layer by layer. However, this method has strong subjectivity and insufficient objective estimation, and how to reasonably integrate objective factors needs further research. At the same time, the life loss, economic loss, social impact and environmental impact assessment index have some fuzziness and uncertainty. Based on the research status at home and abroad, this paper uses ahp-critic method to calculate subjective and objective weights to solve the integration of subjective and objective weights and make the weights of evaluation indicators more reasonable. The extension cloud model is used to solve the problems of randomness, fuzziness and incompatibility of evaluation indicators, and the membership degree of evaluation indicators at each level is determined. Then, a comprehensive evaluation model of extension cloud dam break consequences based on combination weighting is constructed, and the model is applied to practical projects to verify the effectiveness of the model method.

2 Based On the Combined Weighting Method of Ahp-critic

2.1 Construct the Evaluation Index System of Dam Failure Consequences

The result evaluation of dam failure is a complex and comprehensive evaluation system, which should consider not only whether there is a certain relationship between the indicators, but also whether the indicators are representative. Therefore, we must choose the loss factors scientifically and reasonably on the basis of mastering the whole dam-break flood risk consequence system. Following the principles of systematicness, representativeness and scientificity, this paper selects four first-level indicators, namely, life loss, economic loss, social impact and ecological environmental impact, and sets several second-level indicators under each first-level indicator. The evaluation index system is shown in Figure 1.

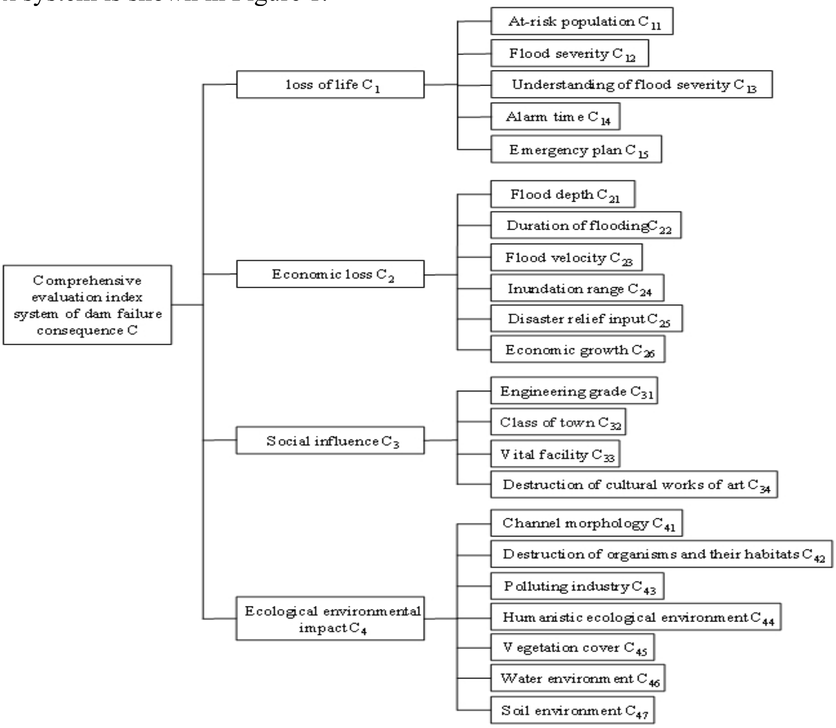

Fig. 1. Comprehensive evaluation index system of earth-rock dam failure loss

2.2 Subjective and Objective Combination Empowerment

1)Improve the subjective empowerment of analytic hierarchy process.

The subjective weight method assigns weights to the importance of indicators based on the senior experience of experts in the field [11]. For the weight calculation of each indicator, the experience of the authority in the neighborhood is indispensable. Therefore, the analytic hierarchy process (AHP) with subjective arbitrariness and uncertainty is adopted to assign subjective weights. When the analytic hierarchy process is used for calculation, 19 scales are mostly used, but the 9-level scale will fail the consistency test, and the decision makers are easy to make contradictory and confusing judgments of relative importance. According to the in-depth research of relevant scholars on the scaling problem, it is suggested to use exponential scaling or to complete the calculation for the ranking problem under multi-criteria with high precision requirements [12].

Considering that there are many evaluation indexes of the result of earth-rock dam failure, and the impact of the result of earth-rock dam failure is huge and the accuracy requirement is high, this paper adopts the subjective weight calculation. The calculation steps are shown in Figure 2.

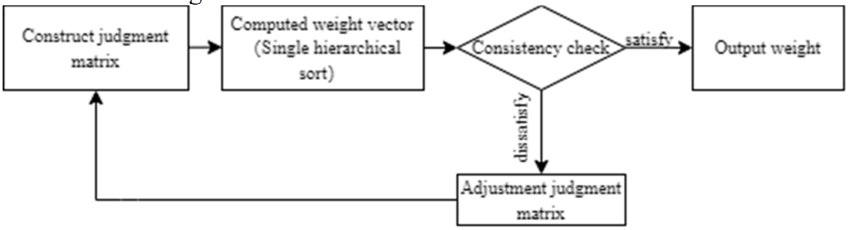

Fig. 2. Calculation of analytic hierarchy process

To calculate the final comprehensive subjective weight value, the calculation formula is as follows:

$$\omega_i = U_i^I \times U_{ij}^{II} \tag{1}$$

ω——Global weight; U_i^I——Level I indicator weight; U_{ij}^{II}——The global weight of a Level II indicator.

2)The objective empowerment of critic.

The objective weighting method is an evaluation method that combines the evaluation index with the sample data to make an objective analysis according to the objective criteria. At present, the main methods used include coefficient of variation, entropy value, critic method, etc. [13]. However, since both coefficient of variation method and entropy method have disadvantages such as the fact that the evaluation results are greatly affected by the sample data, the weight distribution results are not unique, and the correlation before the indicators cannot be reflected, etc., the critic method is adopted in this paper for objective weight assignment.

The weight method of critic proposed by Diakoulak[14] is a method to comprehensively weigh the importance of indicators based on the comparison intensity of evaluation indicators and the conflict between indicators. This method takes into account both the variability of indicators and the correlation among indicators. The larger the number, the more important it is, but the more information contained in each indicator is calculated. If the more information contained in an indicator, the more important the indicator is and the greater the weight should be. The specific calculation steps are as follows:

(1) Calculate the standard deviation of each indicator and the correlation coefficient between indicators.

$$s_i = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(x_{ij} - \overline{x}_i\right)^2} \tag{2}$$

$$\rho_{ij} = \frac{cov(X_i - X_j)}{s_i s_j} \tag{3}$$

x_{ij}——Sample data; m——Sample size; cov（$X_i - X_j$）——Covariance in sample data matrix.

(2) Calculate the information contained in each index.

$$G_j = s_i \sum_{j=1}^{n} (1 - \rho_{ij}) \tag{4}$$

(3) Calculate the objective weights.

$$\beta_i = \frac{G_i}{\sum_{j=1}^{n} G_i} \tag{5}$$

3)Combinatorial weighting based on the principle of minimum information authentication.

The analytic hierarchy process evaluates and analyzes the evaluation system by dividing different levels, which has strong subjectivity and lack of objective data support. critic method uses the objective attributes of data to reflect the conflict and variability among data, but this method is greatly affected by the original data and has strong objectivity. Therefore, combining the advantages of the two weight methods, a new combined weight method is established and the final comprehensive weight is obtained by using the principle of minimum discrimination information [15]. The objective function is shown in formula (6).

$$\begin{cases} \min J(\gamma) = \sum_{i=1}^{n} \left(\gamma_i \ln \frac{\gamma_i}{\omega_i} + \gamma_i \ln \frac{\gamma_i}{\beta_i} \right) \\ \quad s.t. \quad \sum_{i=1}^{n} \gamma_i = 1, \gamma_i \geq 0 \end{cases} \tag{6}$$

s.t.——The mathematical solution to the constraint condition is that the sum of the constraint weights in this paper is 1.

To solve formula (6), the final comprehensive weight is shown in formula (7).

$$\gamma_i = \frac{\sqrt{\omega_i \beta_i}}{\sum_{j=1}^{n} \sqrt{\omega_i \beta_i}} \tag{7}$$

The comprehensive weight vector is $\gamma_i = [\gamma_1, \gamma_2, \cdots \gamma_n]^T$.

3 Evaluation of Dam Failure of Earth-Rock Dam Based on Extended Cloud Model

3.1 Extension Matter-Element Theory

Extension theory was proposed by Professor CAI Wen in the early 1980s to study matter elements and their transformations [16]. Extension is a science that takes contradiction problem as the main research object. It uses formal tools to solve contradiction problem, considers the thing itself, the feature of the thing and the quantity value as a whole, and reflects the change of the thing with matter element transformation. Contradictions can be roughly divided into subjective and objective contradictions (incompatibility), subjective contradictions (opposites), and objective contradictions, which are mainly used to solve incompatibility problems in real life.

3.2 Cloud Model

Cloud model is a kind of uncertainty transformation model between qualitative concepts and quantitative values proposed by Academician Li Deyi in combination with probability theory and fuzzy set theory [17]. The cloud model combines randomness and fuzziness, and expresses the integrity of concepts with three digital features: expectation, entropy and over entropy; expresses the association between randomness and fuzziness through digital feature entropy; and realizes the quantitative transformation of qualitative concepts with a specific generator to reflect the uncertainty of qualitative concepts [17-19].

3.3 Build an Extension Cloud Evaluation Model

The indexes of comprehensive evaluation of dam failure consequences of small and medium-sized earth-rock dams have the characteristics of wide coverage and obvious hierarchy, randomness and fuzzy evaluation indexes, and mutual correlation and influence, but there are certain incompatibility. In order to overcome these problems, the extension matter element analysis method is used to solve the incompatibility between the evaluation indexes and the subordinate process of the indexes in the evaluation index system. However, when the extension analysis method describes the eigenvalue of an object as a constant, it ignores the random fuzziness of the evaluation object itself. To solve this problem, the cloud model can be used to supplement the extension analysis method, and the randomness and fuzziness of the cloud model can be used to improve the extension analysis method to treat the eigenvalue of an object as a fixed value problem. Therefore, this paper makes use of the advantages of the extension cloud model in evaluating things, and applies the extension cloud model analysis method to the comprehensive evaluation of dam failure consequences.

The object characteristics and evaluation index correlation degree in the extension matter element theory are replaced by the standard cloud digital characteristics and cloud membership degree of the cloud model, and the extension cloud evaluation matrix is established. The grade characteristic values in the extension matter-element evaluation model are used to judge the evaluation grade, and at the same time to judge the deviation degree of the evaluation object to the adjacent grade, so as to make up for the shortcomings of the cloud model that it cannot intuitively judge the grade deviation degree. The specific model construction and evaluation steps are as follows:

(1) Calculate the standard cloud characteristic value.

$$\begin{cases} Ex_{ij} = \dfrac{a_{ij}^{1} + a_{ij}^{2}}{2} \\ En_{ij} = \dfrac{a_{ij}^{1} - a_{ij}^{2}}{6} \\ He_{ij} = k \end{cases} \tag{8}$$

(2) Determine the membership function of evaluation index.

$$\mu_x = \exp\left(-\frac{(x-E_x)^2}{2{E_n}^2}\right) \tag{9}$$

(3) Evaluation index of dam failure consequence severity level membership.

$$\mu_v(R) = \sum_{n=1}^{m} \omega\mu_v(R) \tag{10}$$

$\mu_v(R)$——Membership at the corresponding level; ω——Weight value of evaluation index.

(4) Formula (11) is used to calculate the characteristic value of the grade variable of the object to be evaluated.

$$i^* = \frac{\sum_{v=1}^{5} i \times \overline{K_v}(N_i)}{\sum_{v=1}^{5} \overline{K_v}(N_i)} \tag{11}$$

4 Case Verification Analysis

4.1 Evaluation Grade of Dam Failure Consequence of Earth-Rock Dam

According to the regulations on production safety accident reporting and adjustment treatment and the guidelines for the preparation of emergency plan for reservoir dam safety management (Trial), the evaluation indicators of dam failure consequences are divided into five evaluation levels, the quantitative indicators in the evaluation index system are evaluated, and the qualitative indicators are quantified by the number distribution of 0 to 100 within the evaluation range, due to space constraints, some of the results are shown in Table 1.

Table 1. Dam failure consequence evaluation index grade quantification table

index	I	II	III	IV	V
	Minor grade	General grade	More significant grade	Severity grade	Extremely severe grade
C11	0~0.1	0.1~1	1~10	10~50	50~100
C12	0~0.5	0.5~4.6	4.6~12	12~15	15~100
C13	0~25	25~45	45~65	65~85	85~100

4.2 Index Weight Determination

Whether the index weights are reasonable depends mainly on the relative importance of indicators. For subjective weights, in the process of obtaining expert opinions, the differences in the evaluation views of experts in different fields on various indicators are emphatically considered, which greatly simplifies the difficulty of evaluation. For objective weights, dimensionless data is processed before calculation to complete the standardization of indicators. The index weights are determined by comparison, contradiction and information carrying degree, and the weights of the two indicators are compared, as shown in Figure 3. Finally, the principle of minimum discrimination information is used to fuse the weight values obtained by ahp and critic method, as shown in Figure 4, and the calculation results of C1 indicator are shown in Table 2. It can be seen from FIG. 3 and FIG. 4 that the weights of indicators calculated by different weighting methods are different. The principle of minimum discrimination information effectively balances the indicators with large differences in main and objective weights, and solves the problem that the subjective and objective evaluation indicators cannot be unified.

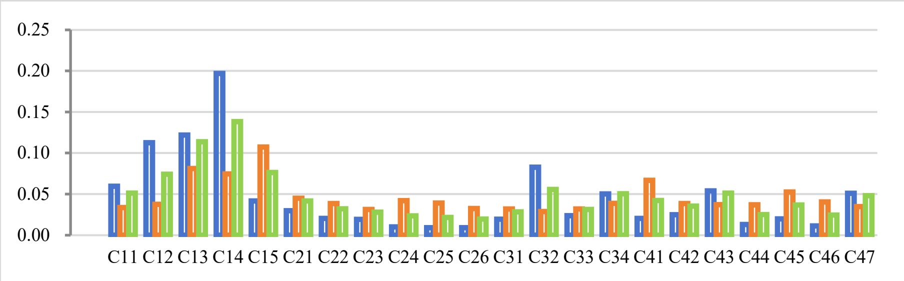

Fig. 3. Index weights under different combination weighting methods

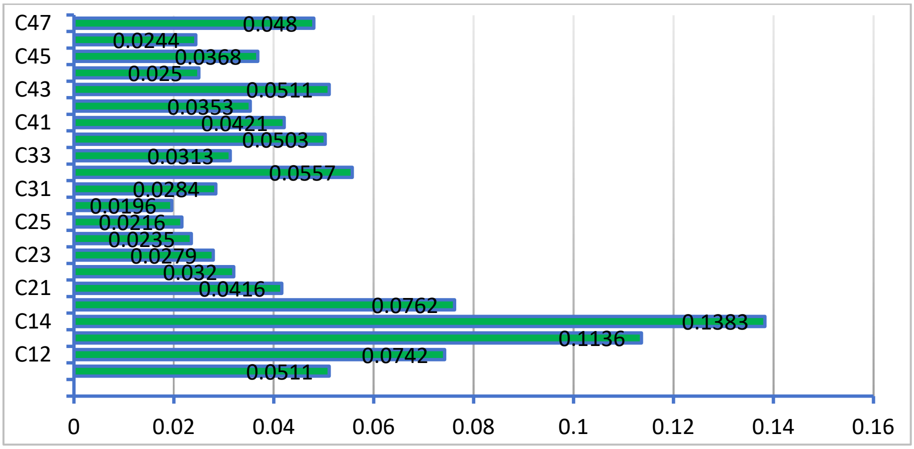

Fig. 4. Weight after optimization of minimum information discrimination principle

Table 2. Index system weight calculation results

Target layer	Primary index	Secondary index	AHP weight	CRITIC weight	Synthesis weight	Assembly weight	weight
Comprehensive evaluation of dam failure consequences of small and medium-sized earth-rock dams	C1	C11	0.0596	0.0336	0.0511	0.1127	0.4534
		C12	0.1125	0.0375	0.0742	0.1636	
		C13	0.1219	0.0812	0.1136	0.2506	
		C14	0.1969	0.0745	0.1383	0.3050	
		C15	0.0416	0.1072	0.0762	0.1681	

4.3 Comprehensive Evaluation of Dam Failure

A reservoir located in the upper reaches of Yilaxi River is a medium-sized reservoir, which is composed of earth dam, flood discharge irrigation tunnel, and very spillway on the right bank. The index value of the reservoir is finally determined according to the length of the dam break, the flow at the dam break and the breach, the water depth, the velocity and the emptying time of the reservoir calculated from the data. Combined with the quantitative table of the evaluation indexes of dam break consequences (Table 1), the cloud model inverse generator is used to calculate the digital characteristic values of the cloud model of the secondary indexes, some of the results as shown in Table 3. Matlab programming and formula (10) were used to calculate the membership degree and grade characteristic values of evaluation indicators at all levels and the final comprehensive evaluation. Some of the results are shown in Table 4, Table 5 and Table 6.

Table 3. Index standard cloud model digital parameters

index	I	II	III	IV	V
	Minor grade	General grade	More significant grade	Severity grade	Extremely severe grade
C11	（0.05,0.0167,0.0017）	（0.55,0.15,0.0150）	（5.50,1.50,0.1500）	（30,6.6667,0.6667）	（75,8.3333,0.8333）
C12	（0.25,0.0833,0.0083）	（2.55,0.6833,0.0683）	（8.3,1.2333,0.1233）	（13.5,0.5,0.05）	（57.5,14.1667,1.4167）
C13	（12.5,4.1667,0.4167）	（35,3.3333,0.3333）	（55,3.3333,0.3333）	（75,3.3333,0.3333）	（92.5,2.5,0.25）

Table 4. Membership degree of secondary evaluation index of dam failure consequences

Secondary index	I	II	III	IV	V	Safety level
	Minor grade	General grade	More Significant grade	Severity grade	Extremely severe grade	
C11	0.0000	0.0000	0.1054	0.1054	0.0000	IV
C12	0.0000	0.0000	0.0000	0.0000	0.2133	V
C13	0.0000	0.0001	1.0000	0.0001	0.0000	III

Table 5. Membership degree of the first-level evaluation index of dam failure consequences

Primary index	I	II	III	IV	V	Safety level	eigen-value
	Minor grade	General grade	More significant grade	Severity grade	Extremely severe grade		
C1	0.1798	0.1359	0.2662	0.0119	0.0349	III	46.1268
C2	0.0525	0.0000	0.0008	0.3613	0.1839	IV	74.8680
C3	0.0036	0.1120	0.0974	0.1570	0.1056	IV	65.3272
C4	0.0000	0.0000	0.1789	0.0496	0.1424	III	62.7109

Table 6. Membership degree of comprehensive evaluation of dam failure consequences

Target layer	I	II	III	IV	V	Safety level	eigen-value
	Minor grade	General grade	More significant grade	Severity grade	Extremely severe grade		
C	0.0908	0.0802	0.1839	0.1045	0.1013	III	60.1768

The calculation of the membership degree of various indexes and different levels is the basis for comprehensive evaluation of the consequences of dam failure of small and medium-sized earth-rock dams. The maximum membership degree is taken as the index evaluation grade. Through the analysis of Table 5, it can be concluded that the dam failure of this reservoir will cause "relatively significant" life loss, "serious" economic loss, "relatively significant" ecological environment impact and "serious" social impact. The severity was grade III, IV, III, and IV respectively, and the grade eigenvalues were biased to grade II, without obvious bias, grade IV, and grade III.

It can be concluded from Table 6 that $\max\mu_v(R)=0.1839$, the severity level of dam break consequence is level III, which is a relatively major accident. According to its grade characteristic value, the severity of dam break of reservoir is between Level II and Level IV, but the severity is inclined to level IV, that is, the severity of dam break consequence of reservoir has a tendency to develop into a serious accident.

5 Conclusion

Small and medium-sized earth-rock dams in China have large base, long service time, serious aging phenomenon and high risk of dam break. The state attaches great importance to water conservancy construction, and focuses on promoting the construction process of small and medium-sized earth-rock dams. Considering the current situation and existing research results, a comprehensive evaluation index system for the consequences of dam break of small and medium-sized earth-rock dams should be established, and the grades of the indicators should be completed. Based on the loss of people's lives and property and the impact on society caused by the consequences of dam break, the loss of life, economic loss, ecological environmental impact and social impact should be taken as the first-level indicators. And construct a number of secondary indexes to establish an evaluation index system; The results show that the evaluation results are reasonable and reliable, which provides a new method and idea for the comprehensive evaluation of dam failure.

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