

Research Article

Research and Application of Critical Failure Paths Identification Method for Dam Risk Analysis

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Received 29 April 2020; Revised 8 August 2020; Accepted 15 September 2020; Published 23 September 2020

Academic Editor: Francesco Clementi

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Dam is an important part of the national infrastructure, and its safety has been widely concerned. Risk identification of dams plays a significant role in risk assessment and control. Finding out some critical failure paths through adopting timely measures can help reduce the risk occurrence probability effectively. This paper develops an identification method based on the credibility and the interval analytic hierarchy process (IAHP) methods, namely, consistency and difference-based interval analytic hierarchy process (CDB-IAHP) method, to identify the critical failure paths of dams exactly considering the dynamic cognition degree of decision-makers. Based on the fault tree analysis (FTA) method, the framework and analysis for critical failure paths identification of a gravity dam and an Earth-rockfill dam are conducted and made. The results show that the critical failure paths obtained by the proposed method are in line with the statistical data, and the importance of disaster causing factors has some difference with the traditional method. Additionally, some engineering and nonengineering measures are suggested to reduce the impact of potential failure paths. The applications demonstrate that the proposed method shows good applicability for risk analysis and critical failure path mining of dams.

1. Introduction

Since the twenty-first century, a large number of dams with a height exceeding 200 m or even 300 m have been built or are under construction, of which Earth dams and gravity dams account for 91%. The safety of high dams has attracted wide attention due to the complex geology condition and changeable environment. According to statistics, there are 3498 dam failure accidents in China with different failure modes. The failure modes are related to the dam type, geological condition, management, and dispatching, such as the failure modes of instability failure of foundation in gravity dams (St Francis gravity dam in the US), the failure modes of dam break (Shimantan dam in China) and seepage damage (Teton, the clay core dam in USA) in Earth dams, and the failure modes of abutment destabilization (Malpasset dam in France) and landslide surge (Vajont dam in Italy) in arch dams. Diversified failure modes pose great

challenges to management. Failure of dams may be avoided through adopting some timely reinforcement measures if the potential critical failure paths could be identified beforehand.

Analytic hierarchy process (AHP) [1, 2] is one of the most widely adopted methods for quantitative analysis of qualitative problems. Because of its simplicity and effectiveness, AHP is widely used in many complex decision-making fields [3–6], including the risk analysis on dams. Choi et al. [7] studied the quantitative evaluation index and evaluation method of dam safety restoration using the AHP method. Li et al. [8] investigated the dynamic risk analysis of a high rockfill dam during construction based on the AHP method. However, there are still some deficiencies and limitations in the application of AHP. For example, the comparative judgment is highly subjective because it highly relies on the opinions of decision-makers who may have limited knowledge and experience of alternative methods.

The limitation would lead to the differences in opinions of decision-makers. Fortunately, scholars have developed some theories and methods to solve the deficiencies of AHP. To better deal with the judgment objectively, fuzzy sets were introduced to express decision-makers' evaluations [9–13]. In the field of water and dams, coupled model of fuzzy sets and AHP was also employed, such as the evaluation of dam breaks [14] and the water quality assessment [15]. In addition, the interval analytic hierarchy process (IAHP) method was widely used in the risk identification of dams [16–18]. Although the subjectivity of comparative judgment can be reduced to a certain extent by using the IAHP method, the traditional judgment weight methods (e.g., the arithmetic average method, the weighted geometric mean method, and the weighted arithmetic average method) seldom take the dynamical decision-makers' comparative matrix into account and ignore their cognitive degree on complex decision problems [19, 20]. To minimize the impact of decision-makers' subjectivity, a credibility index is adopted to display the differences among decision-makers quantitatively [21, 22], and then the consistency and difference degree among decision-makers can be determined. However, there is not much research on the methods for the specific critical path identification in dams, the mining of critical failure path is the key step to evaluate the critical risk factors and failure paths of dams, and using the consistency and difference among decision-makers to determine the critical paths of dams plays an important role in the risk evaluation of dams. Because of this, a method considering the consistency and difference among decision-makers is developed.

The objective of this paper is to propose a method for identifying the critical failure paths of dams considering the consistency and difference of comparative judgments among decision-makers. The main contents of the study are as follows: (a) based on the IAHP method, the consistency and difference degree analysis of the judgment matrices for disaster causing factors in dams are studied, and then the credibility of decision-makers is determined; (b) the subjective weight and objective weight are adopted to reflect the cognitive degree of decision-makers on complex decision problems, and the ranking method is determined; (c) taking the Guandi gravity dam and the Pubugou Earth-rockfill dam as examples. The application of the proposed method in identifying the critical path of the dam was discussed.

2. Methodology

To make full use of the decision-makers judgment matrix on the set of the disaster-causing factors and reduce the influence of decision-makers' subjectivity on failure path identification in dams, the interval analysis hierarchy process (IAHP) combined with the credibility theory, including the consistency and difference (named CDB-IAHP), is introduced to identify the critical failure paths in dams. Based on the fault tree analysis (FTA) method, the CDB-IAHP method integrating the interval analytic hierarchy process, consistency, and difference of decision-makers is applied to a gravity dam and an Earth-rockfill dam. The critical failure

paths of dams are compared with the statistics of failure paths. The methodology is shown in Figure 1.

2.1. IAHP Method. Interval analytic hierarchy process (IAHP) uses quantitative intervals instead of a certain value to describe the relative importance of indexes. The upper and lower limits of quantitative intervals can be determined by a standardized comparison scale of nine levels (Table 1).

Matrix \mathbf{A}_{kl}^p is defined as a comparative judgment matrix based on the hierarchical structure formed by the nine-level method. \mathbf{A}_{kl}^p can be expressed as

$$\mathbf{A}_{kl}^p = [\mathbf{A}_{kl}^{p-}, \mathbf{A}_{kl}^{p+}],$$

$$\mathbf{A}_{kl}^{p-} = (a_{klij}^{p-})_{n \times n}, \quad (1)$$

$$\mathbf{A}_{kl}^{p+} = (a_{klij}^{p+})_{n \times n},$$

$$a_{klij}^{p-} = \frac{1}{a_{klji}^{p+}}, \quad \frac{1}{9} \leq a_{klij}^{p-} \leq a_{klij}^{p+} \leq 9, \quad (2)$$

where \mathbf{A}_{kl}^p represents the judgment matrix for the l^{th} index evaluation set in the k^{th} level from decision-maker p ($p = 1, 2, \dots, m$); m denotes the number of decision-makers; a_{klij}^{p-} and a_{klij}^{p+} represent the upper and lower limits of the relative importance of the indexes i and j for the l^{th} index evaluation set in the k^{th} level from decision-maker p ; k denotes the level number of hierarchical structure; l denotes the number of index evaluation sets in each level.

The judgment matrix often has an important impact on the analysis results, so the consistency test of the interval judgment matrix is needed [23]. For any two interval numbers $\overline{a_{klij}^p} = [a_{klij}^{p-}, a_{klij}^{p+}]$ and $\overline{b_{klij}^p} = [b_{klij}^{p-}, b_{klij}^{p+}]$ in equation (1), the multiplication and reciprocal operation of interval numbers are defined:

$$\overline{a_{klij}^p} \overline{b_{klij}^p} = [a_{klij}^{p-} \cdot b_{klij}^{p-}, a_{klij}^{p+} \cdot b_{klij}^{p+}], \quad \frac{1}{\overline{a_{klij}^p}} = \left[\frac{1}{a_{klij}^{p+}}, \frac{1}{a_{klij}^{p-}} \right]. \quad (3)$$

When $1 \leq i, j, t \leq n$, we have

$$\overline{a_{klij}^p} \overline{a_{kljt}^p} = \overline{a_{kljj}^p} \overline{a_{klit}^p}, \quad \overline{a_{klij}^p} = \frac{1}{\overline{a_{klji}^p}}, \quad \overline{a_{klij}^p} = [1, 1]. \quad (4)$$

Then, matrix \mathbf{A}_{kl}^p can be considered to meet the consistency and \mathbf{A}_{kl}^p is the consistent interval number judgment matrix [24].

2.2. CDB-IAHP Method for Failure Path Identification on Dams

2.2.1. Consistency and Difference Analysis of Weight Data. It is known that there are still some deficiencies and limitations in the application of AHP or IAHP, and the path identification on dams plays an important role in the risk analysis of dams. Although the number of decision-makers is enough and their knowledge and experience are rich,

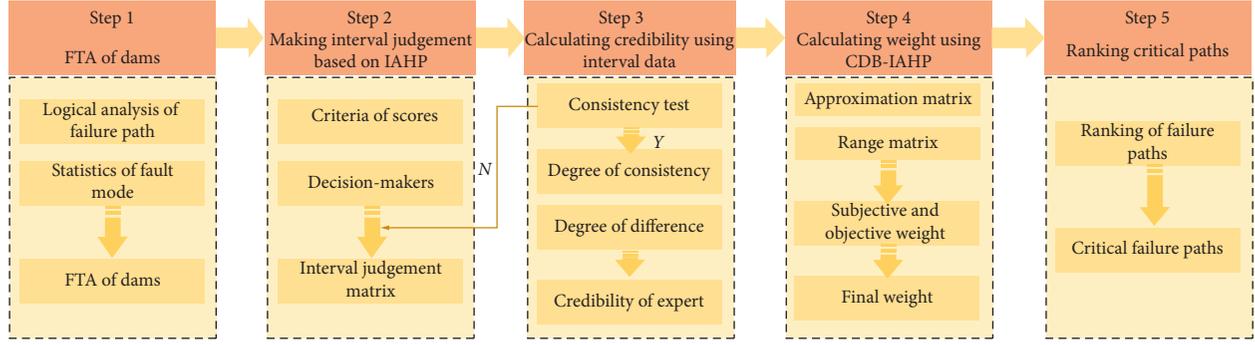


FIGURE 1: Flowchart for the failure paths identification of dams.

TABLE 1: Nine-point intensity of importance scale and its description.

Definition	The intensity of importance scale
Equally important	1
Moderately more important	3
Strongly more important	5
Very strongly more important	7
Extremely more important	9
Intermediate values	2, 4, 6, 8

consistency and difference between judgment matrices based on different decision-makers' opinions for the disaster-causing factors in dams exist objectively.

On one hand, the consistency degree (ω_p) among decision-makers for the disaster-causing factors in dams is often measured by deriving the spatial position relationship between vectors, that is, the cosine value of the angle between two vectors:

$$\omega_p = \frac{\left(\sum_{q=1}^m \left(\left(\frac{A'_{kl}{}^p, A'_{kl}{}^q}{\|A'_{kl}{}^p\| \cdot \|A'_{kl}{}^q\|} \right) - 1 \right) \right)}{\sum_{q=1}^m \left(\sum_{q=1}^m \left(\left(\frac{A'_{kl}{}^p, A'_{kl}{}^q}{\|A'_{kl}{}^p\| \cdot \|A'_{kl}{}^q\|} \right) - 1 \right) \right)}, \quad (5)$$

where $A'_{kl}{}^p$ and $A'_{kl}{}^q$ are the derived vectors of the judgment matrices $A_{kl}{}^p$ and $A_{kl}{}^q$ for l^{th} index evaluation set in the k^{th} level from decision-makers p and q , respectively, and they can be obtained by the following two equations:

$$A'_{kl}{}^p = \left(a'_{kli'j'}{}^p \right)_{1 \times 2n^2} = \left(a'_{kl11}{}^{p-}, \dots, a'_{kln1}{}^{p-}, \dots, a'_{kl12}{}^{p-}, \dots, a'_{kln2}{}^{p-}, \dots, a'_{kl1n}{}^{p-}, \dots, a'_{klnn}{}^{p-}, a'_{kl11}{}^{p+}, \dots, a'_{kln1}{}^{p+}, \dots, a'_{kl12}{}^{p+}, \dots, a'_{kln2}{}^{p+}, \dots, a'_{kl1n}{}^{p+}, \dots, a'_{klnn}{}^{p+} \right), \quad (6)$$

$$A'_{kl}{}^q = \left(a'_{kli'j'}{}^q \right)_{1 \times 2n^2} = \left(a'_{kl11}{}^{q-}, \dots, a'_{kln1}{}^{q-}, \dots, a'_{kl12}{}^{q-}, \dots, a'_{kln2}{}^{q-}, \dots, a'_{kl1n}{}^{q-}, \dots, a'_{klnn}{}^{q-}, a'_{kl11}{}^{q+}, \dots, a'_{kln1}{}^{q+}, \dots, a'_{kl12}{}^{q+}, \dots, a'_{kln2}{}^{q+}, \dots, a'_{kl1n}{}^{q+}, \dots, a'_{klnn}{}^{q+} \right), \quad (7)$$

where $i' = 1$ and $j' = 1, 2, \dots, 2n^2$.

On the other hand, the difference of evaluation value is adopted to express the difference degree among decision-makers; the difference degree σ_p between decision-maker p and other decision-makers can be expressed by

$$\sigma_p = \frac{\bar{\Delta}_p}{\sum_{p=1}^m \bar{\Delta}_p}, \quad \bar{\Delta}_p = \sum_{j'=1}^{2n^2} \left| a'_{kli'j'}{}^p - \bar{a} \right|, \quad \bar{a} = \frac{1}{m} \sum_{p=1}^m a'_{kli'j'}{}^p, \quad (8)$$

where $\bar{\Delta}_p$ denotes the sum of the differences between the judgment matrix of decision-maker p and the mean value; \bar{a} is the mean of the relative importance of each index of different decision-makers.

Therefore, the credibility of decision-makers' evaluation results indicates the difference relationship among

evaluation results which are jointly determined by the consistency degree and the difference degree [25]. The credibility (λ_p) of an expert p can be calculated by

$$\lambda_p = \begin{cases} \omega_p, & \left(\sum_{p=1}^m \omega_p \sigma_p = 1 \right), \\ \frac{\omega_p (1 - \sigma_p)}{1 - \sum_{p=1}^m \omega_p \sigma_p}, & \left(\sum_{p=1}^m \omega_p \sigma_p \neq 1 \right). \end{cases} \quad (9)$$

2.2.2. Ranking of the Failure Paths in Dams. The error theory is a common method to solve interval weights. The interval weights are calculated based on the consistent approximation matrix and range matrix.

Assuming that there is an interval judgment matrix $\mathbf{A} = (A_{ij})_{n \times n}$ ($A_{ij} = [a_{ij}^-, a_{ij}^+]$) for the disaster-causing factors in dams, the consistent approximation matrix and range matrix of matrix \mathbf{A} can be given based on the error theory.

$$\mathbf{M} = (m_{ij})_{n \times n}, \quad (10)$$

$$m_{ij} = \left(\prod_{z=1}^n \frac{a_{iz}^- a_{iz}^+}{a_{jz}^- a_{jz}^+} \right)^{1/2n},$$

$$\Gamma_1 \mathbf{M} = (\Gamma_1 m_{ij})_{n \times n} = (m_{ij} - a_{ij}^-)_{n \times n}, \quad (11)$$

$$\Gamma_2 \mathbf{M} = (\Gamma_2 m_{ij})_{n \times n} = (a_{ij}^+ - m_{ij})_{n \times n}, \quad (12)$$

where matrix \mathbf{M} is the consistent approximation matrix of matrix \mathbf{A} ; and matrices Γ_1 and Γ_2 are the two range matrices of matrix \mathbf{A} .

Based on equations (10)–(12), the weight vectors \mathbf{W} of matrices \mathbf{M} , Γ_1 , and Γ_2 can be expressed as follows:

$$\mathbf{W} = (w_1, w_2, \dots, w_j, \dots, w_n),$$

$$w_j = \frac{(\prod_{z=1}^n a_{jz}^- a_{jz}^+)^{1/2n}}{\sum_{i=1}^n (\prod_{z=1}^n a_{iz}^- a_{iz}^+)^{1/2n}}, \quad (13)$$

$$(\Gamma_t w_j)^2 = \frac{\sum_{i=1}^n (\Gamma_t m_{ij})^2}{(\sum_{i=1}^n m_{ij})^4}, \quad (t = 1, 2).$$

Then, the interval weight w_j' of interval judgment matrices and the specific interval weight $w_j^{p'}$ for decision-maker p can be given by the following two equations, respectively:

$$w_j' = (w_j - \Gamma_1 w_j, w_j + \Gamma_2 w_j) = (w_j^-, w_j^+), \quad (14)$$

$$w_j^{p'} = (w_j^{p-}, w_j^{p+}). \quad (15)$$

Generally, the final weight can be calculated by the arithmetic average method, the weighted geometric mean method, and so forth. However, these results cannot reflect the cognitive degree of decision-makers on complex decision problems. Because of this, the subjective and objective weights are adopted to reflect the subjective aspect and the objective aspect of decision-makers' opinions, respectively, as shown in the following two equations:

$$\omega_{x1} = \frac{1}{2} \frac{\sum_{p=1}^n \left\{ \lambda_p \left[(w_j^{p+})^2 - (w_j^{p-})^2 \right] \right\}}{\sum_{p=1}^n \left[\lambda_p (w_j^{p+} - w_j^{p-}) \right]}, \quad (16)$$

$$\omega_{x2} = \frac{b_{dj}}{\sum_{j=1}^n b_{dj}}. \quad (17)$$

We have $b_{dj} = 1/(1 + g_j)$, $g_j = (1/3) \sum_{p=1}^n \frac{1^n (\lambda_p [(w_j^{p+}) - \omega_{x1}]^3 - [(w_j^{p-}) - \omega_{x1}]^3)}{\sum_{p=1}^n \lambda_p [(w_j^{p+}) - (w_j^{p-})]}$, where ω_{x1} is the subjective weight; and ω_{x2} is the objective weight [26].

Therefore, the final weight ω_x of disaster-causing factors in dams can be expressed as

$$\omega_x = \frac{\omega_{x1} \omega_{x2}}{\sum_x \omega_{x1} \omega_{x2}}. \quad (18)$$

3. Case Studies

3.1. Case A: The Guandi Gravity Dam

3.1.1. Project Review. Guandi hydropower project is located in Liangshan, Sichuan Province. It is composed of a roller-compacted concrete (RCC) dam, a flood discharge structure, an underground powerhouse on the right bank, and so on. The normal water level is 1330.0 m, with a corresponding capacity of 752.8 million-m³. The maximum dam height is 168 m. The elevation of the barrage is about 1334.0 m. The dam crest length is 516.0 m, the lowest base elevation is 1166.0 m, and the maximum dam bottom width is 153.2 m. Guandi hydropower project is located on the West Margin of the Yangtze Paraplatform, with complex cracks under the dam, strong regional neotectonic movement, and relatively stable zone in the near dam reservoir area. The peak acceleration standard of seismic fortification of the dam is 0.2 g, and its upstream and downstream views are shown in Figure 2.

Combined with the failure mode statistics, working principle of gravity dam, and operation performance of Guandi gravity dam, fault tree network of the dam was constructed, as shown in Figure 3.

3.1.2. Weights. Five decision-makers in the fields of design, construction, management, scientific research, and teaching, named DM1 ~ DM5, were invited to judge the failure path index. Table 2 shows the results of the second-level index in Figure 3.

As can be seen from Table 2, there exists a certain difference among five decision-makers when judging the



FIGURE 2: The Guandi gravity dam. (a) Upstream side. (b) Downstream side.

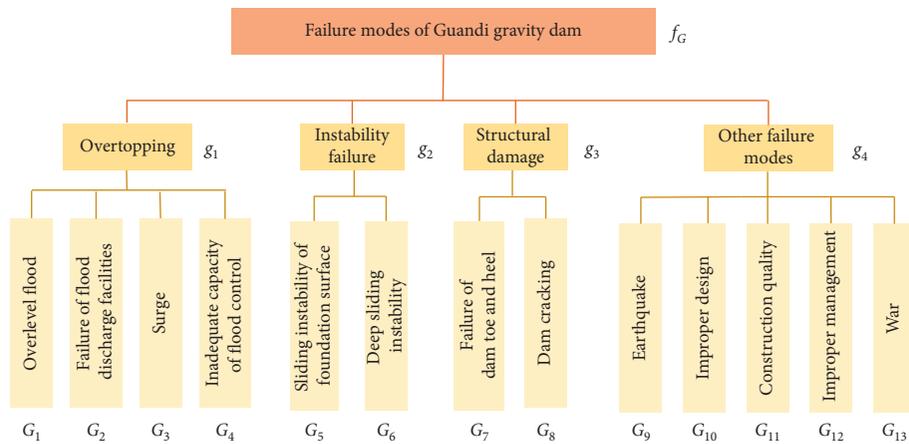


FIGURE 3: Potential failure paths of the Guandi gravity dam.

TABLE 2: Weight results of the second-level index of the Guandi dam.

Decision-makers	Consistency	Difference	Credibility	Interval weight			
				g_1	g_2	g_3	g_4
DM1	0.2033	0.1918	0.2053	(0.5830, 0.5901)	(0.1738, 0.1750)	(0.1918, 0.2130)	(0.0404, 0.0413)
DM2	0.2035	0.1732	0.2102	(0.5379, 0.5991)	(0.1488, 0.1575)	(0.2454, 0.2791)	(0.0506, 0.0512)
DM3	0.2006	0.2002	0.2005	(0.5306, 0.5193)	(0.1165, 0.1480)	(0.2850, 0.3422)	(0.0407, 0.0416)
DM4	0.1990	0.2335	0.1907	(0.4959, 0.5058)	(0.1029, 0.1099)	(0.3527, 0.3806)	(0.0314, 0.0323)
DM5	0.1936	0.2013	0.1933	(0.6195, 0.6305)	(0.1909, 0.2378)	(0.1291, 0.1316)	(0.0375, 0.0381)
CDB-IAHP				(0.5480, 0.5590)	(0.1468, 0.1656)	(0.2403, 0.2690)	(0.0403, 0.0411)
Subjective weight				0.5487	0.1726	0.2909	0.0402
Objective weight				0.2500	0.2500	0.2499	0.2501
Final weight				0.5214	0.1640	0.2764	0.0382

relative importance between any two indexes concurrently. The difference could be caused by their experience, knowledge, subjective will, and other influences. In Table 2, the consistency of five decision-makers' judgment matrices for indexes is not an average of 0.20, which is calculated in a traditional method, but fluctuates from 0.1936 to 0.2035 and with a sum of 1. The credibility of

decision-makers also has changed to an unpredictable value, not a fixed value of 0.20. Additionally, the subjective weights vary considerably, indicating that the proposed method can dynamically take the differences among decision-makers into accounts based on the judgment matrices. The weight results of other indexes are shown in Table 3.

TABLE 3: Weight results of the third-level index of the Guandi dam.

Indexes	Weight	Indexes	Weight	Indexes	Weight	Indexes	Weight
G_1	0.4692					G_9	0.4340
G_2	0.2920	G_5	0.4618	G_7	0.7157	G_{10}	0.1488
G_3	0.1450					G_{11}	0.1166
G_4	0.0938	G_6	0.5382	G_8	0.2843	G_{12}	0.2758
						G_{13}	0.0248

TABLE 4: Final ranking of failure paths of the Guandi gravity dam.

	Second-level indexes	Weight	Third-level indexes	Weight	Path weight	Ranking
Failure paths of Guandi gravity dam	g_1	0.5214	G_1	0.4692	0.2205	1
			G_2	0.2920	0.1687	3
			G_3	0.1450	0.0779	5
			G_4	0.0938	0.0542	8
	g_2	0.1640	G_5	0.4618	0.0757	7
			G_6	0.5382	0.0883	4
			G_7	0.7157	0.1978	2
	g_3	0.2764	G_8	0.2843	0.0786	6
			G_9	0.4340	0.0166	9
			G_{10}	0.1488	0.0057	11
	g_4	0.0382	G_{11}	0.1166	0.0045	12
			G_{12}	0.2758	0.0105	10
			G_{13}	0.0248	0.0009	13

3.1.3. *Ranking.* According to the results of the final weights of indexes and the potential failure path fault tree hierarchical graph of the Guandi gravity dam, the weight ratio of different failure paths could be obtained. Table 4 shows the final ranking of failure paths of the Guandi gravity dam.

The top five critical failure paths of the Guandi gravity dam are the following:

- (1) Overlevel flood \rightarrow overtopping \rightarrow gravity dam failure
- (2) Failure of dam toe and heel \rightarrow structural damage \rightarrow gravity dam failure
- (3) Failure of flood discharge facilities \rightarrow overtopping \rightarrow gravity dam failure
- (4) Deep sliding instability \rightarrow instability failure \rightarrow gravity dam failure
- (5) Surge \rightarrow overtopping \rightarrow gravity dam failure

Table 5 shows the main failure modes of 130 gravity dams according to the failure cases in the world [24–28]. As seen in Table 5, the percentage of overtopping is up to 33.8%, showing that the overtopping is the main disaster-causing factor. The failure modes of structural damage and instability failure also account for a large proportion. The results obtained from the proposed method in the paper are consistent with the statistical data.

The comparative ranking results of the traditional IAHP method and the proposed method in this paper are shown in Figure 4. Results show that the final ranking of most failure paths does not change, while the ranking of failure paths of $G_5-g_2-f_G$ and $G_8-g_3-f_G$ is reversed. Although the ranking is less affected by these two methods, the weight of each level index and the final weight are

different. Taking the final weight for the failure paths as an example, the first three failure paths (①, ②, and ③ in Figure 4) for the Guandi gravity dam are the same by using the IAHP and the CDB-IAHP methods. The final weights are 0.2447, 0.1978, and 0.1522, as well as 0.2542, 0.1593, and 0.1671, respectively, implying that the importance of the critical factors and failure paths is different, which has important engineering significance to take engineering and nonengineering measures to reduce the risk of failure paths.

3.2. Case B: The Pubugou Earth-Rockfill Dam

3.2.1. *Project Review.* Pubugou Earth-rockfill dam is the 17th step in the cascade planning of the mainstream of Dadu River, China. The dam is located near the upper reaches of the Niri River in the middle reaches of the Dadu rivers and across the counties of Hanyuan and Ganluo in the western part of Sichuan Province. The control catchment area is 68512 km², which accounts for 88.5% of the area of the Dadu River basin. Pubugou dam is a large-scale hydropower project mainly for power generation, combined with flood control, and blocking and other comprehensive utilization benefits. The normal water level of the Pubugou dam is 850.00 m, the limiting water level in the flood period is 841.00 m, the dead water level is 790.00 m, and the total storage capacity is 5.39 billion m³, for the incomplete annual regulation of the reservoir, as shown in Figure 5.

Combining with the failure mode statistics, working principle of Earth dams, and the related working performance of the Pubugou Earth-rockfill dam, this paper constructed the fault tree network, as shown in Figure 6.

TABLE 5: Statistics of main failure modes of gravity dams.

Failure modes	Number of cases	Percentage (%)	Reasons
Overtopping	44	33.8	Dam break of the upstream reservoir, heavy rainfall, failure of flood discharge facilities, etc.
Instability failure	22	16.9	Strength weakening of bedrock, curtain damage, scouring, etc.
Structural damage	34	26.2	Earthquake, cracking of dam body, etc.
Other failure modes	16	12.3	War, improper design, poor construction quality, improper management, etc.
Unknown	14	10.8	
Sum	130	100	

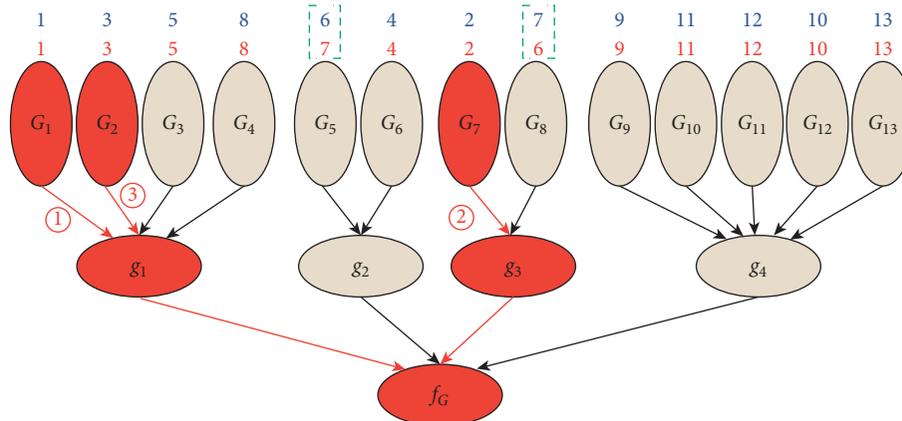


FIGURE 4: Comparison chart of IAHP and CDB-IAHP methods.



FIGURE 5: The Pubugou Earth-rockfill dam.

3.2.2. Analysis and Results. Five decision-makers in the fields of design, construction, management, scientific research, and teaching were also invited to judge the failure path indexes, respectively. As seen in Tables 6 and 7, the application effect of CDB-IAHP in the process of Earth dam failure path identification was similar to that of the gravity dam, and the decision-maker had a dynamic difference to different levels of indexes. The top five critical failure paths of the Pubugou Earth-rockfill dam are as follows. The complete ranking is shown in Table 8; the results also have a good relationship with the statistical results:

- (1) Overlevel flood \rightarrow overtopping \rightarrow Earth dam failure
- (2) Leakage of dam body \rightarrow seepage failure \rightarrow Earth dam failure
- (3) Failure of flood discharge facilities \rightarrow overtopping \rightarrow Earth dam failure
- (4) Crack \rightarrow structural failure \rightarrow Earth dam failure
- (5) Surge \rightarrow overtopping \rightarrow Earth dam failure

According to the embankment dam failures cases [29], the percentage of overtopping of the embankment dam is

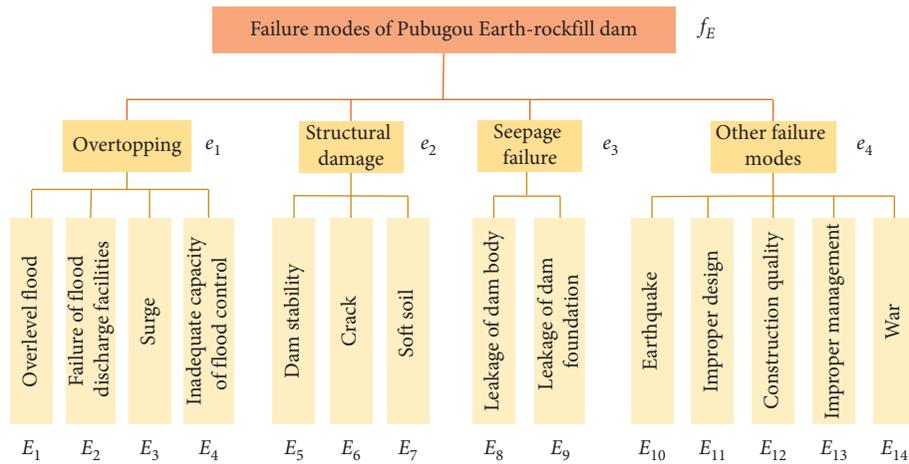


FIGURE 6: Potential failure paths of the Pubugou Earth-rockfill dam.

TABLE 6: Weight results of the second-level index of the Pubugou dam.

Decision-makers	Consistency	Difference	Credibility	Interval weight			
				e_1	e_2	e_3	e_4
DM1	0.2005	0.1945	0.2018	(0.5684, 0.5916)	(0.1671, 0.1675)	(0.1990, 0.2110)	(0.0402, 0.0409)
DM2	0.2000	0.1872	0.2031	(0.5868, 0.5898)	(0.2036, 0.2085)	(0.1637, 0.1643)	(0.0416, 0.0422)
DM3	0.2021	0.1898	0.2046	(0.5594, 0.5622)	(0.1878, 0.1891)	(0.2113, 0.2153)	(0.0405, 0.0412)
DM4	0.2022	0.2011	0.2019	(0.5657, 0.5704)	(0.1300, 0.1311)	(0.2622, 0.2699)	(0.0353, 0.0361)
DM5	0.1953	0.2274	0.1886	(0.4676, 0.4712)	(0.1122, 0.1146)	(0.3826, 0.3857)	(0.0329, 0.0338)
CDB-IAHP				(0.5544, 0.5582)	(0.1609, 0.1630)	(0.2417, 0.2472)	(0.0382, 0.0389)
Subjective weight				0.5585	0.1729	0.2409	0.0381
Objective weight				0.2500	0.2500	0.2499	0.2501
Final weight				0.5528	0.1711	0.2383	0.0378

TABLE 7: Weight results of the third-level index of the Pubugou dam.

Indexes	Weight	Indexes	Weight	Indexes	Weight	Indexes	Weight
E_1	0.5067	E_5	0.1619	E_8	0.7335	E_{10}	0.4037
E_2	0.2848	E_6	0.5224			E_{11}	0.1404
E_3	0.1305					E_{12}	0.1575
E_4	0.0780	E_7	0.3157	E_9	0.2665	E_{13}	0.2736
						E_{14}	0.0247

TABLE 8: Final ranking of failure paths of the Pubugou dam.

Failure paths of Pubugou dam	Second-level indexes	Weight	Third-level indexes	Weight	Path weight	Ranking
		e_1	0.5528	E_1	0.5067	0.2801
E_2				0.2848	0.1574	3
E_3				0.1305	0.0721	5
E_4				0.078	0.0431	8
e_2		0.1711	E_5	0.1619	0.0277	9
			E_6	0.5224	0.0894	4
			E_7	0.3157	0.0540	7
e_3		0.2383	E_8	0.7335	0.1748	2
			E_9	0.2665	0.0635	6
			E_{10}	0.4037	0.0153	10
			E_{11}	0.1404	0.0053	13
			E_{12}	0.1575	0.0060	12
			E_{13}	0.2736	0.0103	11
			E_{14}	0.0247	0.0009	14

41.0%, and the internal erosion including the dam leakage accounts for 26.6%. The comparison results show that the critical failure paths obtained by the proposed method are almost in line with the statistical data.

To reduce the potential impact of the critical failure paths on dams, not just the Guandi gravity dam and the Pubugou Earth-rockfill dam, some engineering and nonengineering measures can be considered, such as the timely monitoring and early warning of a flood, management of power generation and flood discharge (improving spillway capacity), inspection of dam structure and flood discharge facilities, strengthening the monitoring and management of the dam-foundation system and updating the monitoring equipment, reinforcing the safety and stability of the bank slope near the dam, and scientific and reasonable operation management. The applications of Case A and Case B illustrate that the proposed method shows good applicability for risk analysis and critical failure path mining of dams and has high engineering application value.

4. Conclusions

- (1) Reasonable investigation of dam risk analysis is of great significance for dam risk identification, risk early warning, and long-term operation. Based on the IAHP and credibility theory, a consistency and difference-based interval analysis hierarchy process (CDB-IAHP) for critical failure paths identification on dams was proposed in this paper.
- (2) Considering the decision-maker's dynamic cognitive degree to indexes, the consistency and difference among them on indexes were adopted based on the credibility theory to reduce the influence degree of their experience, knowledge, subjectivity, etc. The subjective weights among decision-makers are more obvious than objective weights, indicating that the proposed method can dynamically adjust the credibility according to different indicators based on the corresponding judgment matrices, rather than being a fixed value.
- (3) The feasibility and effectiveness of the proposed method in the identification of critical failure path for gravity dams and Earth dams were verified based on the Guandi gravity dam and the Pubugou Earth-rockfill dam. The results illustrate that the proposed method in the paper shows good applicability for risk analysis and critical failure path mining of dams.

Data Availability

Requests for access to the data of the dam should be made to Kun He, 494097370@qq.com. The calculated data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research was supported by the National Key R&D Program of China (no. 2018YFC0407103).

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