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ORIGINAL ARTICLE

Application of fuzzy analytic hierarchy process in the risk assessment of dangerous small-sized reservoirs

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Abstract There is large number of small-sized reservoirs and widely distributed in mainland of China, but most of them short of management or the security situation is grim. Once the dam break, the loss caused by damage is very serious. Therefore, it is very necessary to look for a general assessment method to monitor the reservoir safety and avoid dam-breaking accident timely. Currently, the common method for reservoirs risk assessment is a traditional approach based on Certainty Criterion, this method can give the overall safety degree by qualitative assessment, which need a large number of monitoring data and mainly suitable for large and medium sized reservoirs. However, vast majority small-sized reservoirs were neglected and had no monitoring equipment, went short of operation statistical data, so it is difficult to assess using the traditional Certainty Criterion. Aiming at the characteristics of small-sized reservoirs, in this paper we proposed the fuzzy AHP assessment method suitable for small-sized reservoirs' risk analysis, which is based on statistics analysis of the wracked small-sized reservoirs and effective identification of risk factors, then verified the applicability and effectiveness of this method by two engineering cases. The result show that this method can be more truly reflect the security status of the reservoir, and also has the reference value and application prospect for dangerous reservoirs reinforcement in future.

Keywords Risk assessment · Fuzzy AHP · Small-sized reservoirs · Reinforcement

1 Introduction

China is the country which has built the larger number of reservoirs in the world, and also has increasingly prominent problem of dangerous reservoirs [1]. The existing reservoirs above 95.4 % are small-sized, and most of them are low and middle embankment dams. Currently, reinforcement work is carried on all over the country, but the related theoretical method of safety behavior evaluation and reinforcement scheme decision of reservoirs falls behind obviously, which influences scientific decisions for the safety management. Once the dam break, it can bring disasters to people living around, therefore the risk assessment or safety assessment of the dam is truly significant for the construction and daily operation of a reservoir. In mainland of China, currently, a traditional approach based on a Certainty Criterion of Dam Safety Assessment (CCDSA) is most widely employed. Specifically, this approach can rank the security level of a reservoir via periodic inspection and diagnosis. Such approach is simple and easily conducted, accordingly, it is very suitable for single project evaluation. However, since the reservoir system is a very complex system and many factors can generate different effects to the reservoir security, moreover, caused by the uncertainties and fuzziness among different factors, the evaluation results by different

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factors are often incompatible. Therefore, new approaches for reservoir risk assessment are worth to be investigated.

At this stage, scholars have done a lot of work in the reservoir risk analysis and assessment research. Gu and He [2] proposed a risk analysis data mining model for identify the threat of reservoir bank landslide to dam safety in reservoir region high slope. In [3], Zhou, according to the failure mode of Shaheji Reservoir, provided a new way for dam risk assessment based on Bayesian network. Lee proposed a long-term risk assessment method which was applied to the Shihmen Reservoir in Taiwan [4]. Kuo et al. [5] were proposed to evaluate large dam overtopping risk by taking into account spillway gate availability. Yan and Hui [6], focus on emergency disposal of reservoir dam in high altitude areas were evaluated using people's lives security, economic and environmental risk criteria. Goes presents some methods of risk analysis in the spillway of Oros Dam by excess of influent flow [7]. Li and Quan [8] aiming at the problem of quantitative assessment in the situation of the landslide group risk, they put forward the methods for dam site scheme comparison based on landslide risk assessment.

At present, most researches are about large reservoirs' risk analysis, the basic methodology and framework for risk analysis of large reservoirs have matured. However, we find that there lacks research on small-sized reservoir risk assessment and analysis. China has been built 97,721 reservoirs, in which there are 93,260 small-sized reservoirs [1]. Compared with large sized reservoirs, small-sized reservoirs have a significant gap in the aspect of management and monitoring facilities. The large reservoirs normally have professional and systematic management and perfect monitoring facilities, can obtain a lot of information for the analysis and evaluation of the dam risk degree. But, small-sized reservoirs often lack or no management, and inadequate monitoring facilities, difficult to obtain information for risk assessment by using traditional quantitative method [9]. Therefore, in this paper, especially aiming at the actual situation carry out risk assessment research work, and proposed a fuzzy AHP method which is applicable to a small-sized reservoir risk assessment and the feasibility of the algorithm is verified by a project case. Research method and results of this paper provide some theoretical basis and inspiration for further study of dangerous reservoirs mechanism and laws, also provide decision basis and technical support for the reservoir reinforcement works, and have a good reference value to solve the similar engineering problems in future.

The rest of this paper is organized as follows: in Sect. 2 we will briefly introduce some background knowledge and CCDSA method evaluation process. Next in Sect. 3, on the basis of analysis the historical data of small-sized reservoirs break, fuzzy AHP risk assessment system will be presented. Introduced another reservoir risk assessment approach: the non-probabilistic reliability method, illustrate the calculation thought and implementation of this method in Sect. 4. Then in Sect. 5, two case study is presented and explained by using fuzzy AHP and non-probabilistic reliability method, and in last section is compared the advantages and disadvantages of the two methods then gives conclusion and discussion.

2 Background knowledge

Currently, Certainty Criterion of Dam Safety Assessment (CCDSA) rating system in China is guided base on "Dam Safety Management Regulations" (released in 1991) and "Dam Safety Evaluation Guidelines" (SL258-2000) [10]. The CCDSA assessment process is as follows:

Firstly, according to the current design and construction standards, carry out on-site quality inspect and geological survey work; secondly, the following seven dam safety items were recalculated: dam flood control capacity, structural safety, seismic capacity, seepage safety, metal structure, quality and operational management; thirdly, qualitative analysis of the seven dam safety items and divided them into three grades. Grade A is completely safe and reliable, can safely operate by design conditions; grade B is basically safe, but there has the flaw, can operate by strengthening the monitoring conditions; grade C is insecurity, exist potential risks. Finally, considering the above seven safety items, qualitative classified the dam: seven safety items have reached the grade A for "first-class dam"; safety items have reached the grade B or above belongs to "second-class dam"; more than one safety items reached the grade C belongs to "third-class dam".

The CCDSA mainly used in large sized reservoir qualitative safety evaluation, but for small-sized reservoir evaluation the content is too complex and don't has extensive applicability, therefore need to seek a suitable method for small-sized reservoirs risk assessment.

AHP approach is a method by constructed judgment matrix and the specific mathematical to determine, and sequence the weight of risk factors, quantitative assessment of index, and this method suitable for this situation which is the decision-making results difficult to directly and accurately measure [11, 12], and its advantage is that it less dependent on subjective of assessor, synthetically compare of the system overall risk level to make a more reliable assessment under the condition of fuzzy or lack data. And the fuzzy AHP is a decision-making method for various factors to make a reasonable, comprehensive and overall evaluation. The fuzzy analytic hierarchy process (FAHP) has been found useful in a wide range of applications. It is used as a tool for information security risk assessment. In

[13], it has been used to solve various multi-criteria decision-making problems. In a classical aviation safety problem, the technical factors using pairwise comparisons by AHP evaluates [14]. A fuzzy AHP approach is proposed to determine the level of faulty behavior risk (FBR) in safety management work systems in [15]. In [16], Sun develops an evaluation model based on the fuzzy AHP and the technique for order performance by similarity to ideal solution, where the vagueness and subjectivity are handled with linguistic values parameterized by triangular fuzzy numbers. Also, a random fuzzy decision making model was proposed based on values at risk in [17].

This study proposed to utilize a fuzzy AHP method for dangerous small-sized reservoirs risk assessment to solve the problems of lack information and environment complicated in process of assessment. It is by risk characteristics analysis and factors identification of the small-sized dangerously weak reservoir, combining classification of risk assessment index and clausal hierarchical division, construct a risk comprehensive evaluation system. According to the expert scoring to determine each index weight, select the appropriate membership function to determine the fuzzy evaluation matrix and then carry out comprehensive risk assessment. It is proved by a practice example, the result shows that this method can be more truly reflect the reservoir actual conditions, to obtain more reliable and reasonable risk level, also can be serviced reinforcement work of the small-sized dangerously weak reservoir.

3 Fuzzy AHP assessment method for small-sized reservoirs

Small-sized reservoirs also known as the service reservoir or farm dam, which have the same risk assessment process as large-sized and medium-sized reservoirs, but due to the lack of information and funds, it is unrealistic that the risk assessment process of small-sized reservoirs is as detail as large and medium-sized reservoirs. Therefore, we need to consider small-sized reservoirs' own characteristics, to find the main safety factors, to simplify the analysis process, in order to facilitate the operation and promotion.

3.1 Identify risk factors of small-sized reservoirs

According to statistics of the wrecked small-sized dams in China (see Table 1), finding that the following reasons cause the dam wreck [18–21]:

(a) Flood control capacity: the inadequate design height, the low spillway capacity and devastating flood causing overtopping are the main reasons for the crash of small-sized reservoirs, accounting for about 50 % of the total crash.
(b) Structural Safety: the crash caused by structural failure as engineering quality problems, including seepage damage of the dam and foundation, dam unstable landslide, spillway failure, the blockage of drain hole.
(c) Operation and Management: extensive management, the obsolete facilities of dam safety monitoring, and improper use and maintenance are also the small-sized reservoirs' crash factors.
(d) Other factors: dam failure cause by such as the caves of termites and rodents, rare earthquake etc.

Establish a structure of small-sized reservoirs risk assessment based on AHP method, the structure is divided into the target, criteria and indicator layer. In consideration of small-sized reservoirs characteristics, only select four indexes as a criteria layer elements to simplify risk assessment which is the greatest impact on safety, while based on CCDSA risk assessment of large sized reservoirs need to consider all seven indexes under normal circumstances. According to the main reason of small-sized reservoirs' failure, selected eleven representative risk factors as the indicator layer elements, with reservoir risk assessment as the target layer; flooding control ability, structural safety, operation and management, and other influencing factors as the criteria layer elements; dam crest ultrahigh, flood discharge capacity, extraordinary flood, seepage, landslide of dam body, spillway failure, culvert failure, improper management, lack of monitoring facilities, earthquake and biological damage as the indicator layer elements, shown in Fig. 1.

3.2 Build the evaluation set

Based on the established risk assessment system, denoted the each risk element of criteria layer as E_i ($i = 1, 2, 3, 4$); each risk element of indicator layer as e_i ($i = 1, 2,\ldots, 11$).

Establish evaluation set, divided every judges into several level properly in order to measure its importance. For small-sized reservoirs' risk characteristics, the risk level simplified into three levels, which are low-risk, medium risk and high risk, respectively representing "the dam is safe and reliable, and can operate normally as designed; the dam is basically safety and can be run under the enhanced monitoring; the dam is unsafe, belongs to dangerous dam", successively denoted as $V = \{V1, V2, V3\}$, where V_1, V_2, V_3, the corresponding values intervals respectively were $[0, 0.3]$, $(0.3, 0.6]$, $(0.6, 1.0]$.

Table 1 The key reasons causing dam failure and corresponding proportion

	Causes of dam failure	Dam failure number	Ratio/%	Explanation
Dam overtopping	Extreme flood	435	12.6	The number of dam overtopping is 1737, the ratio was 50.2 %, the annual average probability of Dam failure is 4.391×10^{-4}
	Insufficient flood discharge capacity	1302	37.6	
Engineering quality	Dam body and foundation seepage	701	20.2	The number of dam failure event caused by quality problems is 1205, accounting for 34.8 %, the annual average probability of dam failure is 3.083×10^{-4}
	Landslide of dam body	110	3.2	
	Spillway	208	6.0	
	Spillway tunnel	5	0.1	
	Culverts	168	4.9	
	Dam body collapse	13	0.4	
Engineering management	Improper management	185	5.3	Including lack of management, over storage, improper use and maintenance, such as build weir on the spillway etc.
	Others	212	6.1	Artificial grilled mouth, bank landslide near the dam, spillway blockage, improper engineering layout etc.

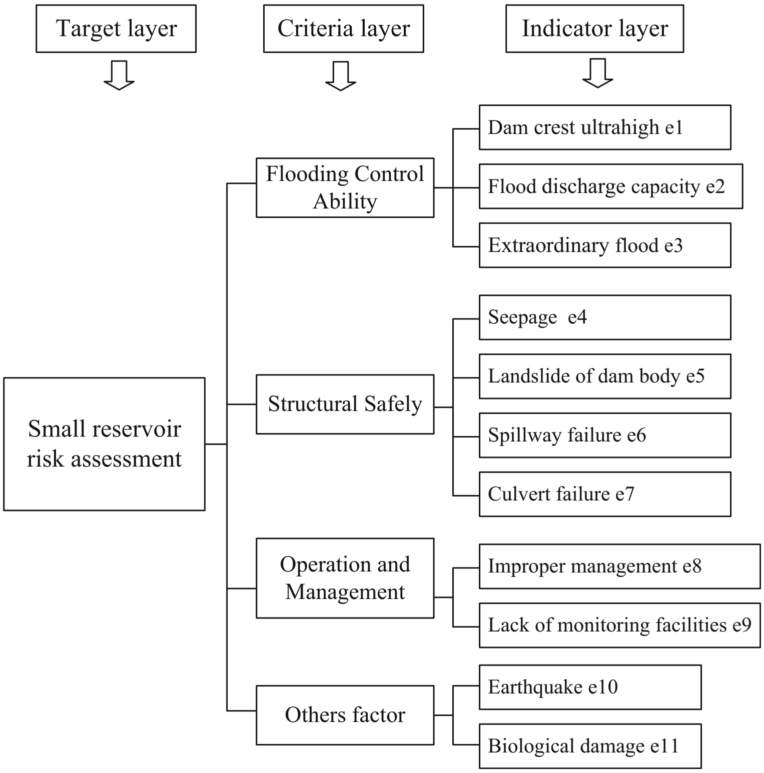

Fig. 1 Structure of hierarchical administrative layers on factors of small-sized reservoir risk assessment

3.3 Obtain membership grade

Because the risk assessment results for each event are fuzzy numbers set on set V, that means the level boundary of evaluate indicators has fuzziness, so it requires use the method of establish grading membership function of each indicators to indicate [22]. For qualitative risk item, according to the relevant order to determine corresponding quantization index shown in Table 2.

For each e_i (i = 1, 2,…, 11) and every risk level V_j (j = 1, 2, 3) has a membership degree and denoted as r_{ij}. For a identified e_i, can evaluate the results by a fuzzy

Table 2 Quantify the impact of risk events

Valuation	Degree/dangerous	Equipment damage
1	Very secure	No
2	Secure	Small
3	Terminate	Large
4	Dangerous	Serious
5	Damage	Fail

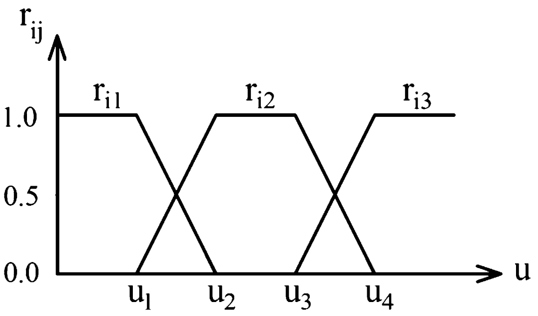

Fig. 2 Trapezoidal membership function distribution (u_1, u_2, u_3, u_4 are the boundary value of three levels of risk)

vector. When each risk factor had been assessed, all evaluation fuzzy vectors constitutes a set of fuzzy relations, that means obtain fuzzy evaluation matrix R:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{im} \end{bmatrix} \tag{1}$$

In this paper, use the membership functions distribute as trapezoidal to determine the membership grade of evaluation matrix index, trapezoidal membership function distribution shown in Fig. 2.

Combined engineering experience and expert scoring to determine each risk factor's membership grade for the risk level of the dam, brought the expert scoring values into the membership function which is risk factors with regard to the risk level, you can get the appropriate membership grade.

3.4 Determine the index's weight based on multi-level analysis method

Since each factor has varying degrees of impact on the division of dam risk criteria, should give each factor with appropriate weights W, and therefore determine the weight of each index is the key issues of small-sized reservoirs risk analysis [23–25]. Based on the analysis of the traditional hierarchical thinking process (AHP), combining the fuzzy mathematics method to create a multi-level fuzzy comprehensive evaluation model for small-sized reservoirs risk analysis.

Table 3 The scale and meaning of matrix judgment

Scale value	Meaning(A than B)
1	Equally important
3	Slightly important
5	Obviously important
7	Strongly important
9	Extremely important

Based on the judgment of the objective risk event, the pair-wise relative importance of elements of each layer should be expressed by the corresponding quantities, constructing the judgment matrix. The 1–9 scales by Saaty T. L. [26, 27] are often used to give an integer in the 1–9 and the last assignment in terms of the the factor's importance affecting the upper layer factor, thereby obtaining the judgment matrix, with scale value meaning shown in Table 3. It should be pointed out that 2, 4, 6, 8, these values represent the mean value between two adjacent scale, and if the importance is in contrast, the scale is its reciprocal.

According to the obtained judgment matrix, then using the square root method to calculate of the corresponding weights:

$$\bar{w}_i = \sqrt[n]{\prod_{j=1}^{n} e_{ij}}(i = 1, 2, \ldots, n)$$

$$W_{Ei} = \frac{\overline{w_i}}{\sum \overline{w_i}} \tag{2}$$

In order to avoid the interference of other factors to the judgment matrix, need to test the judgment matrix's consistency: $CR = CI/RI$, where: CR is the proportion of consistency; CI is the consistency index, $CI = (\lambda_{\max} - n)/(n - 1)$; $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix; n is the row number of the judgment matrix; RI is the average random consistency index.

Through the consistency test obtain the maximum eigenvalue vector of the judgment matrix, which are the weight vectors of risk events:

$$W = [W_{E1}, W_{E2}, \ldots, W_{Ei}] \tag{3}$$

3.5 Fuzzy AHP comprehensive assessment

Using the weight vector W and fuzzy evaluation matrix can get fuzzy comprehensive evaluation subset Y:

$$\begin{aligned} Y = W \cdot R = [W_{E1}, W_{E2}, \ldots, W_{Ei}] \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ r_{i1} & r_{i2} & \cdots & r_{im} \end{bmatrix} \\ = [y_1, y_2, \ldots, y_i] \end{aligned} \tag{4}$$

Evaluate using the maximum membership degree will produce information loss, and thus this paper use the fuzzy weighted method, according to the information interval score which the evaluation set corresponding with, calculate the final comprehensive assessment coefficient Z:

$$Z = \sum_{i=1}^{n} y_i V_i \tag{5}$$

Determine small-sized reservoirs' risk level based on risk level which the comprehensive assessment coefficient Z belongs to.

4 Non-probabilistic reliability theory of small-sized reservoirs risk assessment method

Since most small-sized reservoirs are neglected and have no monitoring equipment, went short of operation statistical data, bring great inconvenience to the risk assessment. However, the non-probabilistic reliability method can be calculated in the absence of data effectively, it's a good attempt for small-sized reservoirs risk assessment [28, 29]. The following is the idea about this method.

While the reservoir water level in front of dam over the crest elevation, water swept over the crest and down causing reservoir break accident. The accident is related to several factors such as crest elevation, dam upstream water level and wave run-up. Therefore, reservoir failure function can be expressed as:

$$G = g(H_{\nabla}, H_m, H_{r+e}) \tag{6}$$

where, G is reservoir function, H_{∇} is dam crest elevation, H_m is dam upstream water level, H_{r+e} is wave run-up.

When $g(H_{\nabla}, H_m, H_{r+e})$ is a continuous function of H_{∇}, H_m, H_{r+e}, function G is interval variable, the non probabilistic reliability index of reservoir can be expressed as:

$$\eta = \frac{G_c}{G_r} = \frac{G^u + G^l}{G^u - G^l} \tag{7}$$

where, η is the non probabilistic reliability index of reservoir, G_c and G_r is the mean value and discrete differential of G, G^u and G^l is the maximum and minimum values of G.

Thus, reservoir overtopping failure risk rate is:

$$P_f = P(G < 0) = \int_{-\infty}^{0} f(G)dG \tag{8}$$

where, P_f is the risk rate of reservoir failure, f (G) is the probability density function of P_f.

In the practical engineering, easy to identify range of the three impact factors which are crest elevation, dam upstream water level and wave run-up, rather than the type of probability distribution. Consequently, the range of these influencing factors can be expressed as:

$$H_{\nabla} \in [H_{\nabla}^l, H_{\nabla}^u]$$
$$H_m \in [H_m^l, H_m^u]$$
$$H_{r+e} \in [H_{r+e}^l, H_{r+e}^u]$$

Using optimization method for solving formula (6) can be calculated the maximum and minimum of function G. The optimization equations show as formula (9) and (10):

$$\begin{cases} G^u = G_{\max} = g(H_{\nabla}, H_m, H_{r+e})_{\max} \\ \qquad\qquad H_{\nabla}^l \le H_{\nabla} \le H_{\nabla}^u \\ s.t. \qquad H_m^l \le H_m \le H_m^u \\ \qquad\qquad H_{r+e}^l \le H_{r+e} \le H_{r+e}^u \end{cases} \tag{9}$$

$$\begin{cases} G^l = G_{\min} = g(H_{\nabla}, H_m, H_{r+e})_{\min} \\ \qquad\qquad H_{\nabla}^l \le H_{\nabla} \le H_{\nabla}^u \\ s.t. \qquad H_m^l \le H_m \le H_m^u \\ \qquad\qquad H_{r+e}^l \le H_{r+e} \le H_{r+e}^u \end{cases} \tag{10}$$

At present, calculated the reservoir failure risk non-probabilistic reliability index η, then according to the theory of non-probabilistic reliability can be calculated the risk ratio by formula (11):

$$P_f = \begin{cases} 0 & \eta > 1 \\ \dfrac{1-\eta}{2} & \eta \in [-1, 1] \\ 1 & \eta < -1 \end{cases} \tag{11}$$

5 Application

Case analysis with two small-sized reservoirs from southeastern and northern Shaanxi Province in China, using fuzzy AHP and non-probabilistic reliability methods for reservoir risk assessment respectively.

5.1 Case 1: *Mozhanggou* reservoir risk assessment

5.1.1 Introduction of Mozhanggou reservoir

Mozhanggou reservoir is located in *Shangluo* mountainous area, southeast of *Shaanxi* Province, the reservoir area watershed is a monsoon climate between the warm temperate zone and north subtropical. Its a small-sized reservoir which control drainage area is 5.1 km^2, total capacity is 770,000 m^3. Reservoir is mainly composed of clay core dam, side channel riverbank spillway, horizontal drainage pipe water and conveyance culverts under dam, dam height is 28.9 m, crest width is 5 m, dam length is 72 m. This reservoir was built in 1973, due to the special historical period, the basic construction system is not perfect, not have the completion and acceptance data. As the reservoir has been extensive management, lack of the dam's corresponding management and operation records, not have any observation facilities. Since the project fell into disrepair for years, there are many security risks, has run in extremely low water, limiting the exertion of the reservoir normal effectiveness. In 2011, *Shangluo* City Water Conservancy Bureau organized experts and technical personnel and conduct site inspection and safety assessment for *Mozhanggou* Reservoir. In early 2012, the Water Authority has invested some funds to reinforce reservoir, and the reinforcement project is nearing completion currently. According to the CCDSA, *Mozhanggou* Reservoir is identified as the third-class dam.

5.1.2 Fuzzy AHP method risk assessment for Mozhanggou reservoir

Using fuzzy AHP method to calculate *Mozhanggou* reservoir risk.

Step 1 Experts and technical staff score risk assessment after the reinforcement, scoring the results in Table 4

Step 2 Calculate assessment matrix

According to the result of expert scoring (Table 4), by the formula (1) and trapezoidal membership function, form the layers fuzzy evaluation matrix of corresponding to Fig. 1.

Each layer's evaluation matrix in reservoir present situation:

$$R_{E1} = \begin{bmatrix} 0 & 0.154 & 0.846 \\ 0 & 0.154 & 0.846 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_{E2} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0.154 & 0.846 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_{E3} = \begin{bmatrix} 0 & 0.154 & 0.846 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_{E4} = \begin{bmatrix} 0 & 0.923 & 0.077 \\ 0 & 0.154 & 0.846 \end{bmatrix}$$

Each layer evaluation matrix in reservoir after reinforcement:

$$R'_{E1} = \begin{bmatrix} 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \\ 0.077 & 0.923 & 0 \end{bmatrix}$$

$$R'_{E2} = \begin{bmatrix} 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \end{bmatrix}$$

$$R'_{E3} = \begin{bmatrix} 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \end{bmatrix}$$

$$R'_{E4} = \begin{bmatrix} 0.077 & 0.923 & 0 \\ 0.077 & 0.923 & 0 \end{bmatrix}$$

Step 3 Calculated judgment matrix

Based on the previous analysis and combine a hierarchical representation (Fig. 1), according to the degree of the risk factors influence on reservoir, with Saaty TL 1 to 9 scale method and Table 3, all factors assigned value (see Table 5), then tested judgment matrix consistency by the formula (2), (3) to obtain the weighted value of each influencing factor, with the results shown in Table 5.

Other items weighted values are following: $WE_1 = [0.4796, 0.4055, 0.1150]$, $WE_2 = [0.4270, 0.4270, 0.0791, 0.0669]$, $WE_3 = [0.5, 0.5]$, $WE_4 = [0.8333, 0.1667]$.

Step 4 Comprehensive assess

According to the calculated criteria layer evaluation matrix in present situation and weight, by the formula (4) there are $Y_{E1} = [0, 0.1363, 0.8638]$, $Y_{E2} = [0, 0.0658, 0.9342]$, $Y_{E3} = [0, 0.077, 0.923]$, $Y_{E4} = [0, 0.7948, 0.2052]$, thus comprehensive assessment matrix of *Mozhanggou* reservoir in present situation is $Y = [0, 0.1505, 0.8497]$. According to the evaluation set corresponding interval value (0.2, 0.5, 0.8), by the formula (5) obtain comprehensive coefficient Z is **0.755**, which belongs to high level risk. The calculation results are consistent with *Mozhanggou* reservoir security evaluation results by traditional qualitative criteria, and consistent with the fact.

In the same way, according to criteria layer evaluation matrix after reservoir reinforcement and weight, by the

Table 4 Expert scoring of the Mozhanggou reservoir risk indexs

Indicator	DCU	FDA	EF	Seepage	LDB	SF	CF	IM	LMF	Earthquake	BD
Present situation	4	4	5	5	4	5	5	4	5	3	4
After reinforcement	1	1	2	1	1	1	1	1	1	2	2

DCU dam-crest-ultrahigh, *FDA* flood discharge ability, *EF* extraordinary flood, *LDB* landslide of dam body, *SF* spillway failure, *CF* culvert failure, *IM* improper management, *LMF* lack of monitoring facilities, *BD* biological damage

Table 5 Values and weights of the criteria layer's judgment matrix

E	E1	E2	E3	E4	W
E1	1	3	7	7	0.5779
E2	1/3	1	5	5	0.2613
E3	1/7	1/5	1	3	0.1022
E4	1/7	1/5	1/3	1	0.0587

formula (4), (5) calculated: $Y_{E1}' = [0.7576, 0.2425, 0]$, $Y_{E2}' = [0.846, 0.154, 0]$, $Y_{E3}' = [0.846, 0.154, 0]$, $Y_{E4}' = [0.077, 0.923, 0]$, comprehensive assessment matrix $Y' = [0.7499, 0.2503, 0]$, obtain comprehensive coefficient Z' is **0.2751**, which belongs to low level risk. This show that by reservoir reinforcement engineering, it's safety risk from high level transfer to low, clear up the potential danger, restore the original function of reservoirs, and ensure the safety of people's lives and property in *Mozhanggou* reservoir downstream.

5.1.3 Non-probabilistic reliability method risk assessment for Mozhanggou reservoir

Using proposed non-probabilistic reliability method to calculate *Mozhanggou* reservoir failure risk.

First of all, according to the available data determined variation range of the three influencing factors: (a) present situation crest elevation is 135.2 m; (b) dam upstream water level: design flood level is 133.99 m, maximum flood level is 134.66 m; (c) the calculated wave run-up and wind backwater height is 0.981–1.142 m. Secondly, put above data into the formula (9), (10), and using optimization algorithms to calculate the maximum and minimum of function G: $G^u = 0.229$, $G^l = -0.602$. Thirdly, using the formula (7) for calculating non-probabilistic reliability index η is -0.449. Finally, according to formula (11) calculated current situation reservoir failure risk ratio P_f is 72.44 %. The results show that current situation reservoir was in the high risk and it couldnot meet the requirements for flood control.

Owing to current situation reservoir risk is quite high, must carry on the reinforcement to reduce potential risk. Thus, the dam had been heightened. Calculation of the dam heightening a certain height to the final heightening height of dam break risk ratio, the results shown in Table 6. It can be seen that in the process of heightening dam height increased from 0 to 0.6 m reservoir risk ratio decreases sharply. Compared with non high, when the dam heightening to 0.3 m risk ratio dropped 36.1 %; when heightening to 0.6 m risk ratio reduced to 0.24 %.

5.2 Case 2: *Huangjiapan* reservoir risk assessment

5.2.1 Introduction of Huangjiapang reservoir

Huangjiapan reservoir is located in *Jingbian* area, northern of *Shaanxi* Province, the reservoir area watershed is semi-arid temperate zone and continental monsoon climate. *Huangjiapan* reservoir control drainage area is 4 km^2, total capacity is 3767,000 m^3, and irrigation area is 3000 mu, design flood control standard for 30-year and 300-year flood to check. Reservoir is mainly composed of homogeneous embankment dam and water release structure, the dam height is 32.8 m, crest width is 6 m, dam length is 117.2 m. Dam upstream average slope is 1:2.5, downstream slope from top to bottom is 1:1.7 and 1:3.5. There were several problems for present situation reservoir: currently reservoir serious silting can only defense the 50-year flood, lack of flood control capacity; dam upstream slope without protection facilities, dam downstream filter have been clogged and lose water filtering function; water release structure was for long years out of repair without seepage capacity; without security monitoring facilities and management cannot effectively monitor reservoir normal operation.

5.2.2 Fuzzy AHP method risk assessment for Huangjiapang reservoir

In the same way, *Huangjiapan* reservoir risk index expert scoring results refer to Table 7.

Calculate assessment matrix. *Huangjiapan* reservoir each layer's evaluation matrix in reservoir present situation:

Table 6 The results of dam heightening and overtopping failure risk calculation

Dam heightening [Δh(m)]	0	0.1	0.2	0.3	0.4	0.5	0.6
Reliability index (η)	−0.449	−0.208	0.032	0.273	0.514	0.755	0.995
Risk ratio P_f (%)	72.44	60.41	48.38	36.34	24.31	12.27	0.24

Table 7 Expert scoring of the *Huangjiapan* reservoir risk indexs

Indicator	DCU	FDA	EF	Seepage	LDB	SF	CF	IM	LMF	Earthquake	BD
Present situation	5	5	4	3	3	5	4	5	5	2	3
After reinforcement	1	1	1	1	1	1	1	1	1	2	2

$$R_{E1} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \\ 0 & 0.154 & 0.846 \end{bmatrix}$$

$$R_{E2} = \begin{bmatrix} 0 & 0.923 & 0.077 \\ 0 & 0.923 & 0.077 \\ 0 & 0 & 1 \\ 0 & 0.154 & 0.8461 \end{bmatrix}$$

$$R_{E3} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_{E4} = \begin{bmatrix} 0.077 & 0.923 & 0 \\ 0 & 0.923 & 0.077 \end{bmatrix}$$

Each layer evaluation matrix in reservoir after reinforcement:

$$R'_{E1} = \begin{bmatrix} 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \\ 0.84 & 0.923 & 0 \end{bmatrix}$$

$$R'_{E2} = \begin{bmatrix} 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \end{bmatrix}$$

$$R'_{E3} = \begin{bmatrix} 0.846 & 0.154 & 0 \\ 0.846 & 0.154 & 0 \end{bmatrix}$$

$$R'_{E4} = \begin{bmatrix} 0.077 & 0.923 & 0 \\ 0.077 & 0.923 & 0 \end{bmatrix}$$

Calculated judgment matrix with the results shown in Table 8.

Other items weighted values are following:

$WE_1 = [0.5192, 0.4337, 0.0471]$, $WE_2 = [0.4591, 0.3814, 0.0942, 0.0653]$, $WE_3 = [0.8333, 0.1667]$, $WE_4 = [0.5, 0.5]$.

Comprehensive assess:$Y_{E1} = [0, 0.0073, 0.9927]$, $Y_{E2} = [0, 0.7858, 0.2142]$, $Y_{E3} = [0, 0, 1]$, $Y_{E4} = [0.0385, 0.9230, 0.0385]$,$Y = [0.0022, 0.2541, 0.7438]$, Z is **0.7225**, which belongs to high level risk. The calculation results are consistent with *Huangjiapan* reservoir security evaluation results by traditional qualitative criteria, and consistent with the fact.

After reservoir reinforcement: $Y_{E1}' = [0.846, 0.154, 0]$, $Y_{E2}' = [0.846, 0.154, 0]$, $Y_{E3}' = [0.846, 0.154, 0]$, $Y_{E4}' = [0.077, 0.923, 0]$, $Y' = [0.8023, 0.1978, 0]$, Z' is **0.2594**, which belongs to low level risk.

Table 8 Values and weights of the criteria layer's judgment matrix

E	E1	E2	E3	E4	W
E1	1	3	9	7	0.5972
E2	1/3	1	5	5	0.2509
E3	1/9	1/5	1	1	0.0950
E4	1/7	1/5	1	1/3	0.0570

5.2.3 Non-probabilistic reliability method risk assessment for Huangjiapang reservoir

In the same way, using proposed non-probabilistic reliability method to calculate *Huangjiapan* reservoir failure risk.

First of all, according to the available data determined variation range of the three influencing factors: (a) present situation crest elevation is 122.5 m; (b) dam upstream water level: design flood level is 121.14 m, maximum flood level is 121.57 m; (c) the calculated wave run-up and wind backwater height is 1.224–1.441 m. Secondly, put above data into the formula (9), (10), and using optimization algorithms to calculate the maximum and minimum of function G: $G^u = 0.136$, $G^l = -0.511$. Thirdly, using the formula (7) for calculating non-probabilistic reliability index η is -0.58. Finally, according to formula (11) calculated current situation reservoir failure risk ratio P_f is 78.98 %. The results show that current situation reservoir was in the high risk and it couldnot meet the requirements for flood control, consistent with the actual situation.

Similarly, the dam had been heightened. Calculation of the dam heightening a certain height to the final heightening height of dam break risk ratio, the results shown in Table 9. It can be seen that in the process of heightening dam height increased from 0 to 0.5 m reservoir risk ratio decreases sharply. Compared with non high, when the dam heightening to 0.3 m risk ratio dropped by half; when heightening to 0.5 m risk ratio reduced to 1.7 %.

6 Conclusion and discussion

The CCDSA method has clear content and strong operability characteristics, and is easy to assess the risk of a single reservoir projects, but assessment results cannot quantitatively reflect the overall severity of the dangerous reservoirs. Compared with CCDSA, fuzzy AHP and non-

Table 9 The results of dam heightening and overtopping failure risk calculation

Dam heightening [Δh(m)]	0	0.1	0.2	0.3	0.4	0.5
Reliability index (η)	−0.580	−0.270	0.039	0.348	0.657	0.966
Risk ratio P_f (%)	78.98	63.52	48.07	32.61	17.16	1.70

probabilistic reliability method were able to carry out a reasonable analysis in case that the information is lack, and to find the limited data to do quantitative calculation. The difference is that fuzzy AHP method can quantitatively consider the influence degree and weight about various risk factors, has more clear logical relationship of uncertainty quantification and special analysis, and the assessment results are more accurate, more reasonable and reliable; however, non-probabilistic reliability method requires only a small amount of influencing factors' uncertainty parameters to realize the risk rate calculation, rather than the exact probability distribution, so it can be used for risk analysis of complex structure such as dam, but it lacks the uncertainty analysis of risk factors. In conclusion, using the fuzzy AHP method to do risk assessment of reservoirs is more feasible.

This paper analysis accident statistics, effectively identify the risk factors of small reservoirs. Then, according to experts scoring of each risk factor, calculate the weight of each factor by the analytic hierarchy process, evaluate the risk of the reservoir using fuzzy mathematical theory, solve the uncertainty problem in evaluation, quantify subjective risk concept and that convenient processing of mathematical model, reduce the difference caused by subjective judgments, so that make the results more accurate and realistic. The methods and results of this research will help find safety problems or weaknesses in reservoirs, provide a theoretical basis for in-depth study of the mechanism of dangerous reservoirs and a good reference for guiding reinforcement work and ensure the safe operation of the reservoir. Develop a more detailed, comprehensive expert grading standards to minimize the subjectivity influence from expert scoring, improve the accuracy of fuzzy multilevel assessment method, all that will be done in future.

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