



A New Approach for Dam Safety Assessment Using the Extended Cloud Model

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Abstract

To address the uncertainty problem in the assessment of the overall safety trend of dams and in the selection of safety trend warning indicators, an Extended Cloud Model (ECM) combined with the Extended Analytic Hierarchy Process (EAHP) method is proposed in this study. In this new approach, different factors reflecting dam safety monitoring have been considered as a fuzzy system. Considering the characteristics of the forward cloud model and the backward cloud model, the original data have been extended to classify the division interval and determine the respective indicators. The weight distribution for each indicator level has been determined using the EAHP method. The model developed was applied to evaluate the safety trend of the Jilintai concrete panel rockfill dam. Simulation results showed that the proposed model can generate reliable results, in addition to being used to assess the uncertainty problem and the safety warning indicator. The proposed model is also more flexible and easier to use than other methods.

Keywords Extended cloud model (ECM) · Extended Analytic Hierarchy Process (EAHP) · Concrete panel rockfill dam · Safety trend assessment

1 Introduction

As the age of the dam increases, certain unsafe factors can arise in the dam, such as the seepage accidents that have occurred in the Northwest Pass Hydropower Station and the Barragrande Hydropower Station. Therefore, using the prototype observation data, based on comprehensive, accurate and reliable safety monitoring data and design information of the corresponding hydraulic buildings, comprehensive analysis of the prediction results of safety monitoring data, for each monitoring index risk factors, the construction of early warning system, in advance or timely warning when abnormalities and alarms are predicted to occur or actually occur, and then form a suitable method for the evaluation of the safety operation of hydraulic buildings, for the early warning of potential safety hazards of dam projects and dam maintenance has a very important significance and practical value.

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There are many factors that affect the safety of dams, and a comprehensive evaluation of dam safety requires the setting of different monitoring indicators. The methods to establish the early warning value of indicators (such as deformation early warning value) are confidence interval method, small probability method and limit state method (Wu and Su 2005; Lei et al. 2011; Wu et al. 2011; Su et al. 2012). Some scholars combined with other theories (Gu et al. 2017) to establish a risk management-based method for formulating deformation warning indicator values for concrete dams based on the risk theory of concrete dams and the method for formulating deformation indicators for structural calculations, and applied it to a hydropower plant to verify the feasibility of the method. However, all these methods have their limitations and shortcomings: the confidence interval method and the typical small probability method only when the observation data series is long and really encounter more unfavorable load combinations, the predicted monitoring index is close to the extreme value, which is not flexible enough, and the probability of failure is not normative to follow, there is a certain subjective empirical; the limit state method must have complete test data of the physical and mechanical parameters of the dam and dam foundation materials when finding the monitoring index of the monitoring effect quantity (Su et al. 2017). The method of formulating early warning indicators for concrete dam deformation based on risk management theory is not flexible enough, and it is necessary to adjust the dam failure mode and path with the downstream socio-economic development and reformulate the early warning values.

The problem of uncertainty will exist in the evaluation of the overall safety trend of dams, and Li et al. (1995) proposed a cloud model theory based on probability theory and fuzzy mathematics to realize the mutual transformation of mapping relationships between qualitative concepts and quantitative evaluation, which can well solve the non-existent qualitative and random nature of the problem. Currently, cloud models have been applied and achieved good results in many fields due to their fuzzy and stochastic properties (Li et al. 2017; Zhang et al. 2014; Yan et al. 2019; Liu et al. 2014; Yan and Xu 2019; Wu et al. 2021; Peng and Deng 2020). There have been many studies on dam safety assessment (He et al. 2020; Jafary et al. 2018; Su et al. 2017; Gu et al. 2022; Yang et al. 2018), but cloud models in comprehensive dam safety assessment started later (Li et al. 2014; He et al. 2016; He and Gao 2018; Fan et al. 2017), the application of traditional cloud models in dam safety evaluation, although it can well rate the dam safety, the results obtained are relatively single, and the indicators reflecting the safe operation of the dam are not clear, and cannot give the results of the proposed early warning values and the weak links affecting the dam safety.

The Analytic Hierarchy Process (AHP) was proposed by Saaty in the 1970s and is commonly used to determine indicator weights (Araujo and Dias 2021; Ho et al. 2021; Radhika et al. 2021; Nouha et al. 2021). When an assessment matrix for comparing indicators is developed based on pairwise comparisons conducted by experts in the field, the resulting weighting factors may have a strong subjective uncertainty due to different experiences and perceptions of different experts. Topology is a discipline that can be used to solve paradoxical problems by creating matter elements and relation elements. The subject, its features and data are considered as three important elements to describe the objective matter. By using intervals instead of discrete values, researchers have combined the traditional AHP with topology to construct an assessment matrix to obtain the weight values of indicators of each level. This method is called the Extended Analytic Hierarchy Process (EAHP), and the indicator weights thus obtained are considered more objective (Dong et al. 2021).

Dam health diagnosis is a complex nonlinear problem with uncertainty, multiple levels, and multiple indicators. The difficulty is firstly to establish a fuzzy system reflecting the

combination of overall dam safety monitoring items, and secondly to solve the problem of uncertainty and stochasticity. This study established a new approach for dam safety assessment using the extended cloud model, using prototype observations and the characteristics of the forward cloud model and inverse cloud model to solve the problem of ambiguity and randomness in safety monitoring, and to obtain the grade classification based on the original data by extending the The evaluation system of safety trend of Jilintai panel rockfill dam was established based on the risk factors of each monitoring index, and the weight distribution of each index level was determined by combining EAHP to form a suitable evaluation method for the safety operation of hydraulic buildings. The ECM-EAHP method has the advantages of high flexibility, high operability, multiple results, small calculation cost and good visualization. In practice, it can well delete and update indicators as needed, or integrate and subdivide some original indicators to generate some needed derived indicators, which are suitable for dam safety monitoring automation platform and can visually display the dam safety trend, and can provide technical support for the integrated system of dam safety automation monitoring and early warning.

2 Assessment System for Safety Trend of Dams

Developing the assessment system for dam safety trend is a complex task. The accuracy of the assessment system depends mainly on the selection of indicators. These indicators should be representative and concise. In engineering practice, the indicators for dam safety assessment should cover the following five parts: environmental variables, dam seepage, dam deformation, face deformation, and stress–strain (Yang et al. 2010a). Considering these criteria, 35 indicators were selected. For instance, among these 35 indicators, the seepage indicators included seepage both in the left and right bank, as well as through the dam body. The selected indicators are presented in Fig. 1 and Table 1.

3 ECM-EAHP Assessment Method

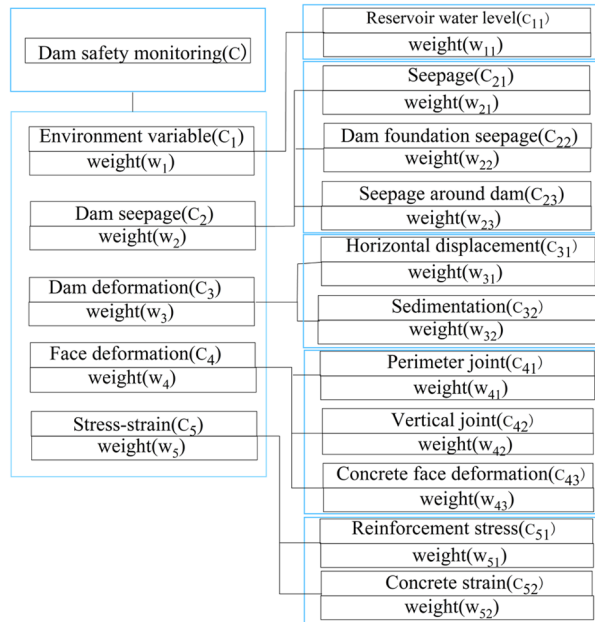
3.1 Concepts and Numerical Characteristics of the Cloud Model

Setting up a quantitative universe U which is represented by an exact value C is a qualitative concept on U . If $\forall x \in U$ and x is a one-time random event on the qualitative concept C , the certainty degree of x on C is a random number with a stable propensity, and x is called a cloud drop (Li et al. 1995)

$$\mu = \exp \left[-\frac{(x - E_x)^2}{2(E_n)^2} \right] \quad (1)$$

The cloud model has three important characteristics: expectation (E_x), entropy (E_n), and hyper entropy (H_e). Expectation (E_x) is the symmetrical axis of the cloud model and represents the most likely events, which are the most typical sample events. Entropy (E_n) is a representation of the uncertainty of the events, which is the range of cloud drop values that the qualitative concept can assume. The hyper entropy (H_e) represents the uncertainty of the cloud droplets. It is the thickness of the cloud level. The relationship between expectation (E_x), entropy (E_n) and hyper entropy (H_e) in the cloud model are shown in Fig. 2a.

Fig. 1 Mapping of assessment for the dam safety



3.2 Introduction to the Extended Cloud Model (ECM)

The ECM is based on the reciprocal transformation of qualitative concepts and quantitative relationships using both forward and inverse cloud models. In the process of

Table 1 Indicators and corresponding factors

Reservoir water level C_{11}	DC-1-01 (C_{111})	Seepage C_{21}	WE-1 (C_{211})
Dam foundation seepage C_{22}	P-1-06 (C_{221})	Seepage around the dam C_{23}	UP-1-13 (C_{231})
	P-1-26 (C_{222})		UP-1-24 (C_{232})
	P-1-30 (C_{223})		SY-1 (C_{233})
	P-1-31 (C_{224})		UP-1-08 (C_{234})
Horizontal displacement C_{31}	ID-1-02 (C_{311})	Sedimentation C_{32}	UP-1-29 (C_{235})
	ID-1-11 (C_{312})		TC-1-11 (C_{321})
	ID-1-13 (C_{313})		TC-1-14 (C_{322})
Perimeter joint C_{41}	JR-1-02-1 (C_{411})	Vertical joint C_{42}	TC-1-18 (C_{323})
	JR-1-07-1 (C_{412})		J-1-12 (C_{421})
	JR-1-09-2 (C_{413})		J-1-22 (C_{422})
	JR-1-10-2 (C_{414})		J-1-27 (C_{423})
	JR-1-02-3 (C_{415})		Reinforcement stress C_{51}
JR-1-11-3 (C_{416})	R-1-10 (C_{512})		
Face deformation C_{43}	TM-1-04 (C_{431})	Concrete strain C_{52}	R-1-13 (C_{513})
	TM-1-11 (C_{432})		S3-1-02-3 (C_{521})
	TM-1-20 (C_{433})		S3-1-05-1 (C_{522})
-	-	-	S3-1-09-2 (C_{523})

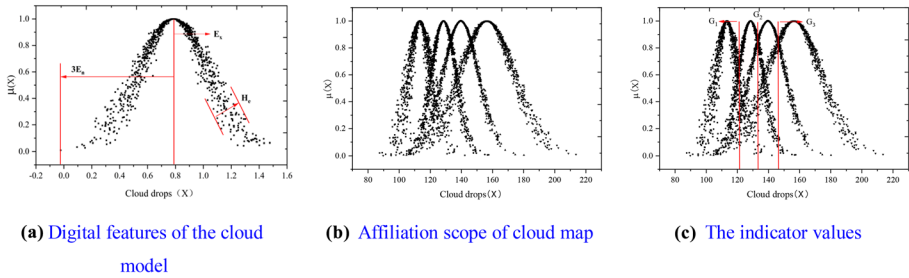


Fig. 2 (a) Graph of numerical characteristics of CM and (b), (c) ECM index value selection

transforming the forward cloud model from the qualitative concept to quantitative relationship, the cloud drops of unfavorable events in the cloud map are divided into affiliation scope according to the principle of 3σ , and the inverse cloud model is reapplied to transform them into qualitative concepts (levels 1 to 4). From the new qualitative concept (levels 1 to 4), the forward cloud model is again used to complete two transformations from the qualitative concept to the quantitative relationship. The index values of each level are obtained from the perspective probability of occurrence, and the index Extended Cloud Diagram is shown in Fig. 2b.

Indicator values can be obtained by extracting the cloud drops of neighboring classes with a distance between two cloud drops less than 0.5 and 0.05 in horizontal and vertical coordinates, respectively. The expected value of their horizontal coordinates is taken as the indicator value, as illustrated in Fig. 2c for G_1 , G_2 , and G_3 .

3.3 EAHP

3.3.1 Extended Analytic Hierarchy Process Steps

The matrix for pair-wise comparisons was constructed according to the scale (b_{ij}) proposed by Saaty and Zhang (2016) and the judgment principle. By using the 1~9 scale to define intervals instead of discrete values, where 1 means equally important, 9 means the former is far more important than the latter, and the other numbers take values in between, the judgment matrix $B = [b_{ij}]_{max}$ ($i, j = 1, 2, \dots, m$) has been constructed, where $b_{ij} = [b_{ij}^-, b_{ij}^+]$ is an interval. For indicators describing the same attribute, to assess the importance of each indicator by using pair-wise comparison, such as the assessment of m indicators inside of the subset $C = \{C_1, C_2, C_3, \dots, C_m\}$ by using a range of importance scales to represent judgment results based on experts' experience, and the values are taken at the symmetrical positions of the judgment matrix (Eq. (2)).

$$b_{ji} = 1/b_{ij} = \left[1/b_{ij}^+, 1/b_{ij}^- \right] \tag{2}$$

Equation (3) shows the pair-wise comparison matrix.

$$B = \begin{bmatrix} \langle 1, 1 \rangle & \langle b_{12}^-, b_{12}^+ \rangle & \cdots & \langle b_{1m}^-, b_{1m}^+ \rangle \\ \langle \frac{1}{b_{12}^+}, \frac{1}{b_{12}^-} \rangle & \langle 1, 1 \rangle & \langle \cdots \rangle & \langle b_{1m}^-, b_{1m}^+ \rangle \\ \langle \cdots \rangle & \langle \cdots \rangle & \langle \cdots \rangle & \langle \cdots \rangle \\ \langle \frac{1}{b_{1m}^+}, \frac{1}{b_{1m}^-} \rangle & \langle \frac{1}{b_{2m}^+}, \frac{1}{b_{2m}^-} \rangle & \langle \cdots \rangle & \langle 1, 1 \rangle \end{bmatrix} \quad (3)$$

3.3.2 Determination of Indicator Weights

If λ^-, λ^+ are the maximum eigenvalues of matrix B , then $\lambda = [\lambda^-, \lambda^+]$ is the interval eigenvalue of the matrix B . By setting $x = [x^-, x^+]$ to be the maximum eigenvector corresponding to the maximum eigenvalue of B .

$$\tilde{x}^- = \left(\sum_{j=1}^m \frac{b_{1j}^-}{\sum_{j=1}^m b_{ij}^-}, \sum_{j=1}^m \frac{b_{2j}^-}{\sum_{j=1}^m b_{ij}^-}, \dots, \sum_{j=1}^m \frac{b_{mj}^-}{\sum_{j=1}^m b_{ij}^-} \right)^T \quad (4)$$

$$\tilde{x}^+ = \left(\sum_{j=1}^m \frac{b_{1j}^+}{\sum_{j=1}^m b_{ij}^+}, \sum_{j=1}^m \frac{b_{2j}^+}{\sum_{j=1}^m b_{ij}^+}, \dots, \sum_{j=1}^m \frac{b_{mj}^+}{\sum_{j=1}^m b_{ij}^+} \right)^T \quad (5)$$

In order to calculate the indicator weights, further normalization of \tilde{x}^-, \tilde{x}^+ is done as follows. Equations (6) and (7) show the minimum and maximum eigenvectors.

$$x^- = (x_1^-, x_2^-, \dots, x_m^-)^T \quad (6)$$

$$x^+ = (x_1^+, x_2^+, \dots, x_m^+)^T \quad (7)$$

Equation (8) is used to assess the consistency of a matrix. The permissible range of inconsistency of a matrix will be determined by using the consistency test.

$$\alpha = \sqrt{\sum_{j=1}^m \frac{1}{\sum_{i=1}^m b_{ij}^+}}, \beta = \sqrt{\sum_{j=1}^m \frac{1}{\sum_{i=1}^m b_{ij}^-}} \quad (8)$$

If $0 \leq \alpha \leq 1 \leq \beta$, the matrix meets the consistency condition. If the consistency condition is not satisfied, the original judgment matrix should be reviewed until the condition is satisfied.

3.3.3 Uniformization of Interval Weight

The weight vector of the interval judgment matrix can be expressed by Eq. (9).

$$S_{ij} = [S_{ij}^-, S_{ij}^+] = [\alpha x_{ij}^-, \beta x_{ij}^+] = \begin{pmatrix} \alpha x_1^- & \beta x_1^+ \\ \vdots & \vdots \\ \alpha x_m^- & \beta x_m^+ \end{pmatrix} \quad (9)$$

Then $V(S_{ijk} > S_{ijl}) \geq 0$ indicates the probability (P_{ijk}) of $S_{ijk} > S_{ijl}$. The probability (P_{ijk}) is calculated as follows by using the simple associative series method,

$$\left\{ \begin{array}{l} P_{ijl} = 1 \\ P_{ijk} = V(S_{ijk} \geq S_{ijl}) = \frac{2(s_{ijk}^+ - s_{ijl}^-)}{(s_{ijk}^+ - s_{ijk}^-) + (s_{ijl}^+ - s_{ijl}^-)} \end{array} \right. \tag{10}$$

where, $i, j = 1, 2, \dots, m$, P_{ijk} denotes a single ranking of k indicators for the ij level of indicators. The weights ω_{ijk} are obtained after normalization

$$w_{ijk} = \frac{P_{ijk}}{\sum_{k=1}^m P_{ijk}} \tag{11}$$

3.3.4 Index Factor

Different assessment indicators have different units. To obtain a reliable assessment, the actual value of each indicator factor (X) was transformed into a fractional value (Q_i) according to the indicator value, calculated as defined in Eqs. (12) and (13).

$$\left\{ \begin{array}{ll} Q_i = 100 & X \leq G_1 \\ Q_i = 100 - \frac{10(X - G_1)}{(G_2 - G_1)} & G_1 < X \leq G_2 \\ Q_i = 90 - \frac{10(X - G_2)}{(G_3 - G_2)} & G_2 < X \leq G_3 \\ Q_i = 80 - \frac{20(X - G_3)}{3(G_3 - G_1)} & G_3 < X \end{array} \right. \tag{12}$$

where, G_1, G_2 and G_3 are indicator value 1, indicator value 2 and indicator value 3, respectively.

$$Q = \sum_{k=1}^l \sum_{j=1}^n \sum_{i=1}^m Q_{ijk} \times \omega_{ijk} \tag{13}$$

where, m is the total number of indicators at the criterion level, n is the total number of factors at the indicator level for a subset of the criterion level, and l is the total number of factor levels for a subset of the indicator level.

4 Health Diagnosis Method of Jilintai Panel Rockfill Dam

Jilintai I Hydropower Station is one of the important hydropower projects in the middle reaches of Kashagr River, located in the middle of Jilintai Gorge section of Kashagr River to the east, as shown in Fig. 4. The site of Jilintai I hydropower station is located in a "V" shaped valley with a topographic slope of about 45° on both sides and a valley width of 340 m. The normal storage level of the hydropower station is 1420 m, and the top of the right bank is about 327~362 m higher than the left bank. The weathering layer is 3~5 m thick and 25~30 m thick, with stable lithology and high rock strength, and the slope is 38°~45°. There are low-order north-west, north-east and north-north-east faults in the section. F32, F32-1, F285 and other low-order faults with a greater impact on the dam site are 295°~340°NE∠35~75°, with a fracture zone of 0.5~22 m, with breccia and fractured rock as well as a small amount of faulted mud and mylonite in the fracture zone.

The concrete panel of Jilintai dam which is located in Xinjiang is made of C30W12F300 concrete with water-cement ratio less than 0.45 and slump of 3~7 cm, as showed in Fig. 3.

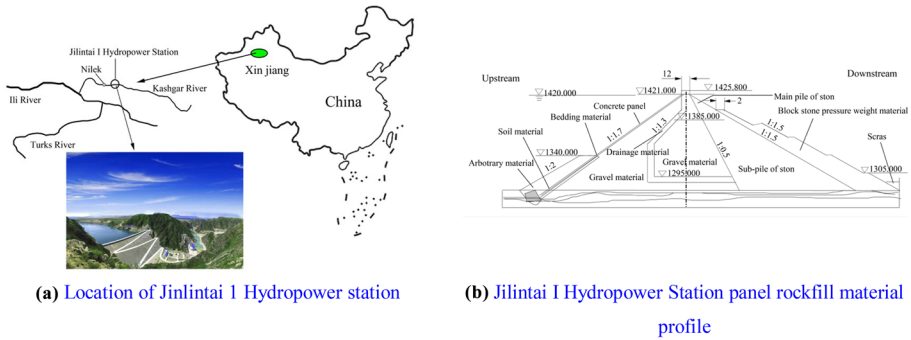


Fig. 3 Jilintai panel rockfill dam location and dam fill material profile

Emulsified asphalt is used as a temporary protective layer to ensure the compactness and smooth surface of the bedding material and to reduce the influence of foundation restraint (Wen and Liao 2004).

During the operation of Jilintai hydropower station, temperature affects the seepage volume and panel deformation. Seepage volume is mainly affected by the reservoir water level and temperature, seepage volume increases with the rise of reservoir water level and decreases with the increase in temperature. It is reported that the impact of the reservoir water level component accounts for about 75% of the annual variation of seepage volume, temperature component accounts for about 5%, and other accounts for about 20%

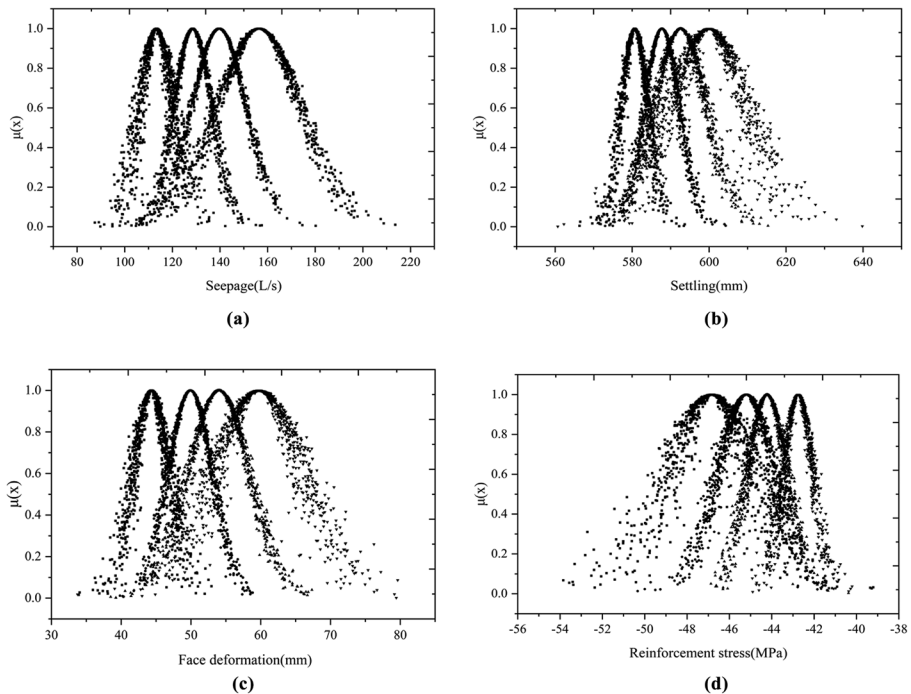


Fig. 4 Indicators for extended cloud model

(Li et al. 2010). The deformation of the panel varies with temperature. In summer, as the temperature rises and the increase in reservoir water level, the compression of the compressive joints in the middle of the panel increases, and the tension of the tension joints on both banks tends to be stable; in winter, both the temperature and the reservoir water level decreases, the compression of the vertical joints in the panel decreases, and the tension of the tension joints increases (Yang et al. 2010b).

4.1 Application of the ECM-EAHP

When using the ECM generator, considering the uncertainty and randomness during the calculation process using the cloud model, 30,000 cloud drops were used to generate the cloud map. The process was repeated 50 times, and the average of these calculations was selected as the final cloud map. In total, there are 35 indicators, and each indicator has one extended cloud map. The extended cloud maps for four indicators are presented in Figs. 4a–d.

The values of the factor indexes are obtained from the extended cloud diagram which show the index values of seepage volume, settlement volume, panel deflection deformation, and steel stress. where the Seepage: $G_1 = 117.20L/s$, $G_2 = 127.44L/s$, $G_3 = 139.20L/s$; Settling: $G_1 = 583.67$ mm, $G_2 = 589.37$ mm, $G_3 = 596.88$ mm; Face deformation: $G_1 = 46.53$ mm, $G_2 = 52.99$ mm, $G_3 = 57.58$ mm; reinforcement stress: $G_1 = -43.85Mpa$, $G_2 = -45.48Mpa$, $G_3 = -47.17Mpa$.

4.2 Calculation Indicator Weights

Based on the results described above, the judgement matrix was determined, as shown in Table 2.

Values in Table 2 were obtained by using Eqs. (4)–(7). The corresponding eigenvectors:

$$x^- = [0.2675 \ 0.2340 \ 0.1982 \ 0.1593 \ 0.1412] \tag{14}$$

$$x^+ = [0.2713 \ 0.2288 \ 0.1933 \ 0.1618 \ 0.1449] \tag{15}$$

According to the Eq. (8), the summation value is calculated to test the consistency of the Extended interval number judgment matrix, with the results of (Guideline level): $\alpha = 0.94$, $\beta = 1.05$. From the results, both α and β satisfy $0 \leq \alpha \leq 1 \leq \beta$, and the consistency test for the judgment matrix is satisfied. The eigenvectors x^- , x^+ for the indicator level are substituted into Eqs. (9)–(11) to calculate P_p and are then normalized to determine indicator single

Table 2 Judgement matrix and weights for level 1

Indicator level 1	C_1	C_2	C_3	C_4	C_5	Weight
C_1	<1.0,1.0>	<1.1,1.2>	<1.3,1.5>	<1.6,1.9>	<1.7,2.0>	0.3211
C_2	<0.83,0.91>	<1.0,1.0>	<1.18,1.25>	<1.3,1.58>	<1.55,1.67>	0.3036
C_3	<0.67,0.77>	<0.8,0.85>	<1.0,1.0>	<1.19,1.3>	<1.31,1.50>	0.2176
C_4	<0.53,0.63>	<0.63,0.77>	<0.77,0.84>	<1.0,1.0>	<1.06,1.30>	0.1035
C_5	<0.5,0.59>	<0.6,0.76>	<0.67,0.76>	<0.77,0.94>	<1.0,1.0>	0.0542

level weights. Similarly, other indicator (in Table 1) for single level weights are obtained, as shown in Fig. 5.

4.3 Calculation of Indicator Level Scores

Taking the raw indicator data into Eq. (12) allows obtaining the assessment scores of the indicators. Taking these assessment scores into Eq. (13) allows obtaining the assessment scores of the indicator level and the overall assessment scores, shown in Figs. 6a–d.

The developed CM-EAHP model has been used for the safety assessment of the Jilintai concrete panel rockfill dam Results showed that due to the decrease in the reservoir water level and the repair projects of the Jilintai dam in recent years, seepage decreased gradually. Results indicated that both the seepage through the dam body and around the dam shoulders is in a safe range, which is consistent with the results obtained from the model calculation.

There was a partial landslide in the back slope of the dam. According to data collected from the automated monitoring system, the horizontal displacement of the dam body has an increasing trend in the past two years. The dam settlement is stable, which may explain the gradual decrease in the local dam deformation score (C_3) from the model monitoring. Overall, it can be concluded that this concrete face rockfill dam is in good condition, and this assessment agrees with the model results (C).

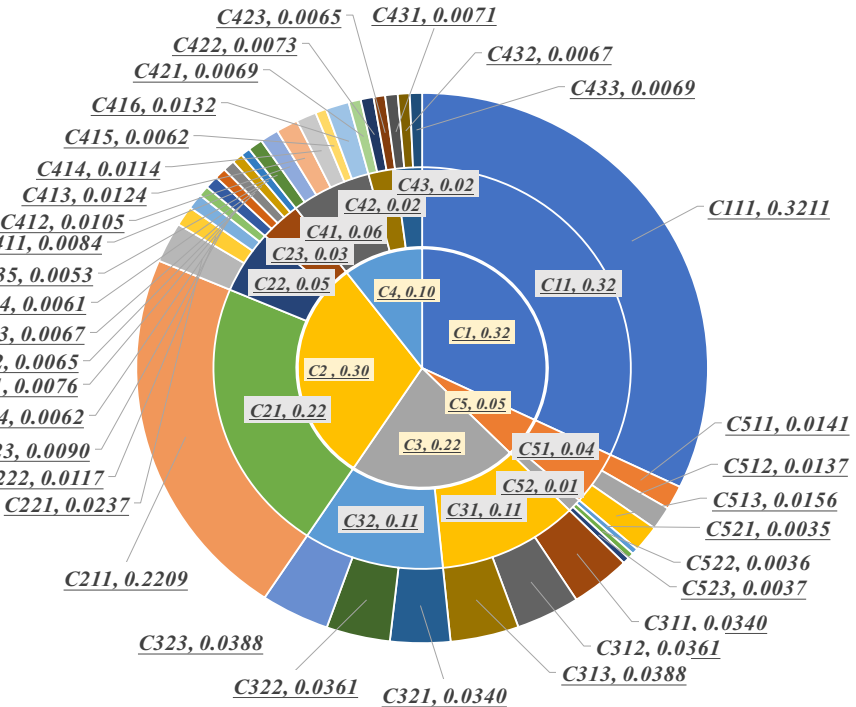


Fig. 5 Indicator weights

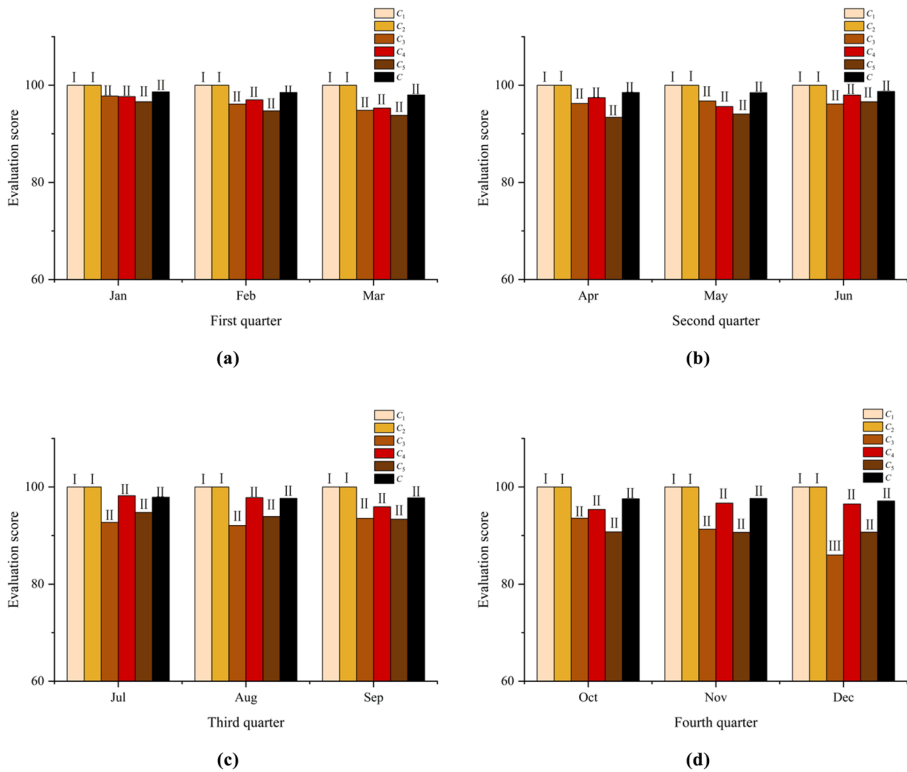


Fig. 6 Score chart for dam safety trend in 2020 – (a) – (d) identify the quarters in the year

4.4 Comparison of Results Using Different Models

4.4.1 The Cloud Model (CM)

The CM assessment method is usually comprised of the following three steps (Zhang et al. 2014): step 1, selection of the original data of the assessment indicators in order to process the cloud transformation; step 2, the establishment of the cloud model of the assessment indicators; and steps 3, comparison of results based on the cloud model of the comprehensive assessment and those of the cloud model of the assessment indicator set. Figure 7a illustrates the process.

From the results shown in Figs. 6 and 7b, it can be seen that assessment results of the operation using both the ECM-EAHP method, and the CM method are both level 2, implying that the assessment results are consistent. One can say that the ECM-EAHP method is feasible and effective, and more comprehensive than the traditional dam safety assessment methods which only give one overall result of the assessment level. Additionally, the ECM-EAHP method is more flexible, and can provide more detailed information such as indicator values. Also, the indicator values can be updated as the data is selected and can provide rapid feedback and early warning of the dam’s current condition when more adverse conditions are encountered.

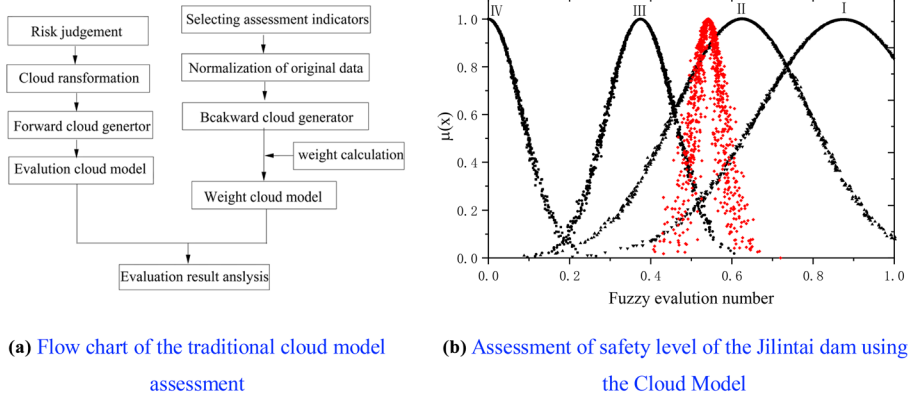


Fig. 7 Traditional cloud model evaluation process and results

4.4.2 Typical Small Probability Method

The early warning results obtained by using the ECM method were compared to those obtained by using the typical small probability method (Wu and Lu 1989). For the water level indicator, the early warning value obtained using the typical small probability method ($\alpha=2\%$) was 1419.93; the early warning value obtained using the ECM was 1420.24. Also, for the horizontal displacement indicator, the early warning value obtained using the typical small probability method ($\alpha=2\%$) was 94.067; and the early warning value obtained using the ECM was 94.101. These results showed that one can get nearly the same results by using the typical small probability method and the Extended Cloud Model method. However, the Extended Cloud Model is more flexible and less computationally expensive.

5 Conclusions

Dam safety assessment is a complicated process which should consider multi-factors, multi-levels, stochastic and fuzzy aspects. The Cloud Model (CM) can better transform the uncertainty and stochastic qualitative aspects during the dam safety monitoring process into quantitative results. In the present study, the ECM-EAHP method has been developed and applied to assess dam safety trend of the Jilintai concrete panel rockfill dam.

Assessment results by using both the ECM-EAHP method and the CM method showed that the operation level of the Jilintai concrete face rockfill dam is level 2. Results of both methods indicate that the Jilintai concrete face rockfill dam has a good operating condition. The horizontal displacement of the dam body has an increasing trend in the past two years. Results showed that other indicators were in a safe operating condition. The selection of indicator values was consistent with the results of the typical small probability method. The cloud model assessment method is mostly a one-time assessment, and the workload is greater if a secondary assessment process should be conducted. The ECM-EAHP method is a visual assessment method for assessing dam safety trends. The ECM-EAHP method not only provides an overall assessment of the dam's safety level, but also provides a detailed visualization of the dam's operating conditions reflected by each factor. The ECM-EAHP method can be combined with an automated dam safety monitoring platform to visualize dam safety trends, providing a methodological

option for an integrated system of automated dam safety monitoring and early warning. The results obtained by applying the proposed method may be useful for the dam maintenance and become more fashionable in other engineering fields, such as the structural field.

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Availability of Data and Materials Availability of data and materials: all data and materials are available upon the requirement.

Declarations

Human and Animal Rights and Informed Consent The study does not involve the use of humans or animals.

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Conflict of Interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article. This manuscript is an original research work. This manuscript has never been submitted to other journals and conferences for possible publication. There is not any interest that is directly or indirectly related to this research work. There is not any potential conflict of interest.

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