

Risk evaluation of tailings dam-break based on the extension matter-element model

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Abstract. As one of the most concerned risk sources of mining enterprises, the safety and stability of the tailings storage facility (TSF) is closely connected to the operating activity, surrounding ecological environment, and residents' lives safety and properties safety. In order to evaluate the risk of the tailings dam break, the extension matter-element model has been applied in the work. First, the risk evaluation indicator system was established, included 3 levels, 4 criteria and 17 individual indicators. Next, the weight of each indicator was computed by using the analytic hierarchy process (AHP) method. Then, the classical field, controlled field and closeness function within the extension matter-element model were determined considering the TSF height and volume, and the principle of the maximum membership degree has been improved by the closeness. Finally, a case study was illustrated to demonstrate the effectiveness of the model. The result indicated that the target TSF operated at a relatively lower risk level, which accurately reflected the real operating situation. This work can provide a reasonable reference for dam break risk evaluation.

1 Introduction

This Tailings is one of the waste byproducts of mining and mineral processing, from which the useful minerals have been extracted. The tailings storage facility (TSF) is a complicated geotechnical engineering structure, which is surrounded by natural heights and/or artificial walls and used to store tailings [1]. Its ultimate purpose is to provide safety, stable, erosion-resistant, non-polluting and economical storage of fine-grained tailings, often with a secondary or co-purpose of conserving water for use in the mine and mill. Therefore, it is obvious that the safety and stability of the whole structure is critical.

In recent years, the hazards of TSF have become increasingly prominent. There have been many TSF accidents around the world [2, 3], according to statistics, about 130 TSF accidents have occurred around the world since 1960 [4]. The consequences involve irreversible surrounding ecological damage and environment damage, lives and properties loss and even social instability [5, 6]. For example, one of the most publicized TSF dam break is the accident that occurred on 8 September 2008, in Xiangfen County, Shanxi Province, China, with 281 deaths, 33 injuries and a direct economic loss of 96.19 million RMB, has been the most tragic reported failure in China so far [7]. On November 5, 2015, Samarco's Fundão tailings dam in Brazil suddenly collapsed. This incident generated 50-60 million cubic meters of mine tailings into the Gualaxo do Norte, resulted in three communities flooded and 19 loss of lives, and affected the biodiversity across hundreds of kilometers of water, which is considered to be the largest environmental disaster of this

type in recent years [8-12]. As a dangerous source of man-made debris flow with high potential energy, the risk evaluation of tailings dam break is a fundamental and practical way to anticipate potential problems and issues.

Up to now, many risk evaluation approaches have been generated, such as the AHP, uncertain measurement, back propagation neural network, fuzzy theory, leading to numerous meaningful research results [13-16]. Majority of contributions in this research field only focused on the qualitative perspective or the quantitative one, and failed to solve the problem of risk evaluation from both the qualitative and quantitative perspective. To make up for this research deficiency, this work adopt extension matter-element model combined with AHP method to evaluate the risk of the tailings dam break. The extension matter-element model established by Chinese scholar W Cai [17] could deal effectively with the intrinsic multidimensionality, complexity and subjectivity of risk evaluation problems. And, the qualitative indicators are able to quantified conveniently by this model. Accordingly, the extension matter-element model is an ideal model for risk evaluation of the tailings dam break.

2 Extension matter-element model for risk evaluation of the tailings dam break

2.1 Selecting a Template (Heading 2) Indicator system of risk evaluation

Establishing an accurate, comprehensive and effective indicator system is the foundation for risk evaluation of the tailings dam break. Given the complicated and variable

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characteristics of the influencing factors, indicators from initiatives, standards, and former literature [18-24] are referred and reorganized in this work. The risk evaluation indicator system for the tailings dam break is divided into

four major criteria: human factor, technology factor, environment factor and management factor, and each criterion is consisted of several individual indicators, shown in Fig 1.

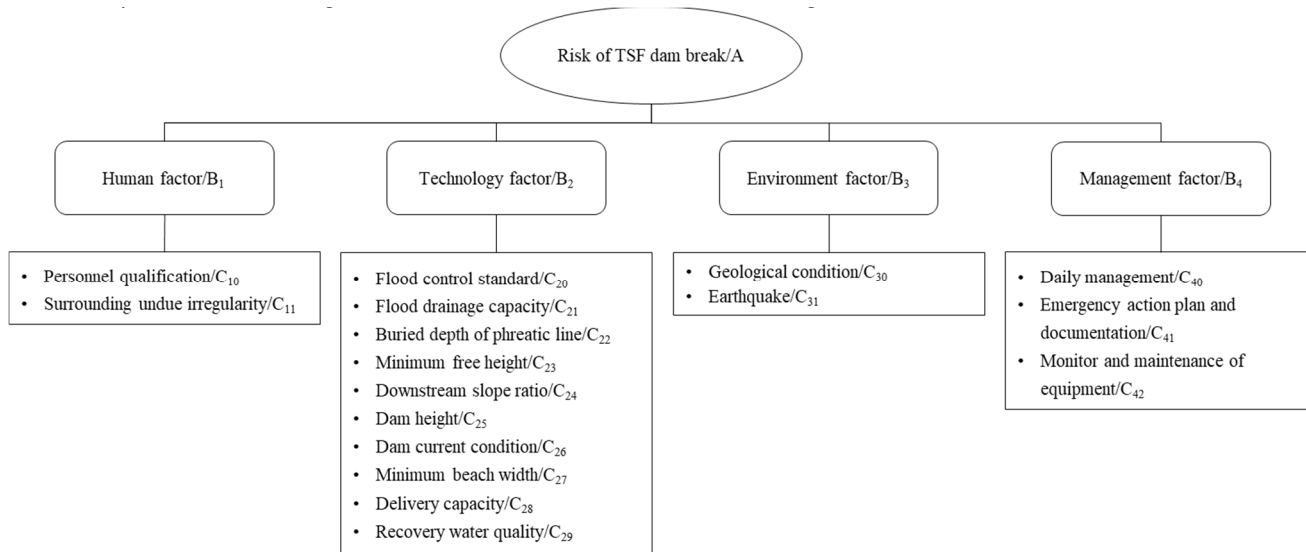


Fig1. Risk evaluation indicator system for the tailings dam break

2.2 Extension matter-element evaluation model

The extension set theory and the matter-element method are the theoretical pillars of the extension theory. The matter-element model is comprised of objects, characteristics and values based on certain characteristics, so as to describe the contents and relationships among evaluation items. The idea of extension matter-element model is that, firstly, the evaluation object (the risk of the tailings dam break) is divided into four levels (lower, low, high, higher) according to existing data and the ranges of data at all levels are given by database or expert opinions. Then a multi-indicator system is measured through inducing the indicators of evaluation objects into the set of each level. The evaluation results are determined according to the value of the closeness function. The greater the degree of closeness is, the better the degree of coincidence is. The specific steps of the evaluation model are shown as follows [25].

Step1 Basic definition

Suppose object N has n characteristics c_1, c_2, \dots, c_n and the corresponding values v_1, v_2, \dots, v_n . Then matter-element R is named n -dimensional matter-element, shown as:

$$R = (N, C, V) = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} = \begin{bmatrix} N & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \quad (1)$$

where R_i is the sub-matter-element of R , C is the eigenvector, V is the value of the eigenvector.

Step 2 Determine the matter-element to be evaluated, the classical field and controlled field

Suppose

$$R_0 = \begin{bmatrix} N_0 & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \quad (2)$$

where N_0 is the matter-element to be evaluated and v_1, v_2, \dots, v_n are the detected concrete data of N_0 about c_1, c_2, \dots, c_n respectively.

Suppose

$$R_j = \begin{bmatrix} N_j & c_1 & v_{j1} \\ & c_2 & v_{j2} \\ & \vdots & \vdots \\ & c_n & v_{jn} \end{bmatrix} = \begin{bmatrix} N_j & c_1 & \langle a_{j1}, b_{j1} \rangle \\ & c_2 & \langle a_{j2}, b_{j2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{jn}, b_{jn} \rangle \end{bmatrix} \quad (3)$$

where N_j is the j levels, c_1, c_2, \dots, c_n are n different characteristics of N_j , and $v_{j1}, v_{j2}, \dots, v_{jn}$ are respectively the value ranges of N_j about c_1, c_2, \dots, c_n , that is the classical field.

Suppose

$$R_p = \begin{bmatrix} N_p & c_1 & v_{p1} \\ & c_2 & v_{p2} \\ & \vdots & \vdots \\ & c_n & v_{pn} \end{bmatrix} = \begin{bmatrix} N_p & c_1 & \langle a_{p1}, b_{p1} \rangle \\ & c_2 & \langle a_{p2}, b_{p2} \rangle \\ & \vdots & \vdots \\ & c_n & \langle a_{pn}, b_{pn} \rangle \end{bmatrix} \quad (4)$$

where N_p is all the levels of objects to be assessed, and $v_{p1}, v_{p2}, \dots, v_{pn}$ are the value ranges of N_p about c_1, c_2, \dots, c_n , namely the controlled field of N_p respectively.

One of the foundations of the risk evaluation of the TSF dam break is the determination of the classical field. With reference to previous existing documents, the risk is divided into four levels, namely L_1 (Lower risk), L_2 (Low risk), L_3 (High risk), L_4 (Higher risk). The specific value ranges of the classic field and the controlled field are shown in Table 1.

Table1. The range of individual indicator for TSF dam break

Individual indicator	TSF grade/ (I-V)	Range of classical field				Rang of controlled field
		L_1	L_2	L_3	L_4	
C ₁₀	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₁₁	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₂₀	I	2000-2500	1500-2000	1000-1500	500-1000	500-2500
	II	1000-1250	750-1000	500-750	250-500	250-1250
	III	500-650	350-500	200-350	100-200	100-650
	IV	200-250	150-200	100-150	50-100	50-250
	V	100-125	75-100	50-75	25-50	25-125
C ₂₁	I-V	30-50	50-72	72-76	76-80	30-80
C ₂₂	I	4.5-6.0	3-4.5	1.5-3	0-1.5	0-6.0
	II	4-4.5	2.5-4	1-2.5	0-1	0-4.5
	III	3.7-4	2.2-3.7	0.7-2.2	0-0.7	0-4
	IV	3.5-3.7	2-3.5	0.5-2	0-0.5	0-3.7
	V	3.4-3.5	1.9-3.4	0.4-1.9	0-0.4	0-3.5
C ₂₃	Dam height 5-10m	2-2.5	1.875-2	1.75-1.875	0-1.725	0-2.5
	Dam height 10-20m	2.5-3	2.25-2.5	2-2.5	0-2	0-3
	Dam height 20-30m	3-3.5	2.75-3	2.5-2.75	0-2.5	0-3.5
	Dam height >30m	4-5	3.5-4	3-3.5	0-3	0-5
C ₂₄	I-II	130-150m	113-130	100-113	0-100	0-150
	III	100-120m	80-100	60-80	0-60	0-120
	IV	60-75m	45-60	30-45	0-30	0-75
	V	30-40m	22.5-30	15-22.5	0-15	0-40
C ₂₅	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₂₆	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₂₇	I	250-300	200-250	150-200	0-150	0-300
	II	180-220	140-180	100-140	0-100	0-220
	III	130-160	100-130	70-100	0-70	0-160
	IV	90-110	70-90	50-70	0-50	0-110
	V	60-70	50-60	40-50	0-40	0-70
C ₂₈	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₂₉	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₃₀	I-V	0.8-1	0.35-0.8	0.05-0.35	0-0.05	0-1
C ₃₁	I-V	0.5-9	5.9-7	7-8	8-10	0-10
C ₄₀	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₄₁	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1
C ₄₂	I-V	0.75-1	0.5-0.75	0.25-0.5	0-0.25	0-1

Step 3 Normalization

However, if the quantified value of any indicator exceeds the controlled field, it will be unable to be calculated. In this case, the matter-element and extension model cannot be used to evaluate the risk levels involved. On the account, the extension matter-element model has been improved, in order to resolve this limitation [26]. This has been done as follows.

$$R'_0 = \begin{bmatrix} N_0 & c_1 & \frac{v_1}{b_{p1}} \\ & c_2 & \frac{v_2}{b_{p2}} \\ & \vdots & \vdots \\ & c_n & \frac{v_n}{b_{pn}} \end{bmatrix} \quad R'_j = \begin{bmatrix} N_j & c_1 & \langle \frac{a_{j1}}{b_{p1}}, \frac{a_{j1}}{b_{p1}} \rangle \\ & c_2 & \langle \frac{a_{j2}}{b_{p2}}, \frac{a_{j2}}{b_{p2}} \rangle \\ & \vdots & \vdots \\ & c_n & \langle \frac{a_{jn}}{b_{pn}}, \frac{a_{jn}}{b_{pn}} \rangle \end{bmatrix} \quad (5)$$

Step 4 Closeness calculation

$$D_j(v'_i) = \left| v'_i - \frac{a'_{ji} + b'_{ji}}{2} \right| - \frac{1}{2}(b'_{ji} - a'_{ji}) \quad (7)$$

$$P_j(R'_0) = 1 - \frac{1}{n(n+1)} \sum_{i=1}^n D_j(v'_i) \omega_i(X) \quad (8)$$

where $D_j(v'_i)$ is the distance of the normalized matter-element evaluation relative to the normalized classical field, $P_j(R'_0)$ is the comprehensive closeness of the j level, $\omega_i(X)$ is the indicator weight, n is the number of indicators.

Step 5 Level determination

Suppose

$$P_m(R'_0) = \max [P_j(R'_0)] \quad (9)$$

where the matter-element to be evaluated R_0 is belonged to the m level.

$$\bar{P}_j(R'_0) = \frac{P_j(R'_0) - \min [P_j(R'_0)]}{\max [P_j(R'_0)] - \min [P_j(R'_0)]} \quad (10)$$

where $\max [P_j(R'_0)]$ represents the maximum of correlation degree in all levels, $\min [P_j(R'_0)]$ represents the minimum of correlation degree in all levels.

$$j^* = \frac{\sum_{j=1}^m j \bar{P}_j(R'_0)}{\sum_{j=1}^m \bar{P}_j(R'_0)} \quad (11)$$

where j^* is the risk level variable eigenvalue of R_0 . The attributive degree of the evaluated matter-element tend to adjacent levels can be judged from j^* .

3 Case study

3.1 Project overview

Shandong Laiwu Luzhong mining company limited has operated for over 30 years. Yujiakuan tailings pond put into operation synchronously with the company, is located 8-12 kilometers north of Laiwu City. There is no harmful geological effect in the study area, such as landslides, avalanches, mud-rock flow, surface subsidence, fall of ground. The Laiwu region is situated at the continental semi-humid monsoon climate in warm temperate zone, with low rainfall intensity, averaging 760.9 mm for many years.

The starter dam of the TSF is constructed by rock and 30 meters high, the accumulation dam is filled upstream style by tailings, which has been widely used in China. Flood drainage system adopts the form of both the drainage well and bottom drainage pipe, and eight drainage wells are set up altogether. The present drainage system is well structured and can meet the requirement of normal backwater and flood control. The TSF has played a good role in reducing the buried depth of the phreatic line in the dam by using waste rock to construct wide sub-dam. In view of the TSF safety management, the relevant facilities and equipment in the surrounding area are under good condition, satisfying the requirements of daily operation and management. In summary, it is implemented in the actual safety production management and meets the safety management requirements.

3.2 Determine the matter-element to be evaluated

According to the engineering background of Yujiakuan TSF, referring to relevant design, construction, and evaluation documents, the value of each indicator is determined, shown in Table 2.

Table2. Indicator value of Yujiakuan TSF

Indicator	C ₁₀	C ₁₁	C ₂₀	C ₂₁	C ₂₂	C ₂₃	C ₂₄	C ₂₅	C ₂₆
Original value	0.75	0.8	1000	30	0.7	5	1:4.0	82	0.85
Indicator	C ₂₇	C ₂₈	C ₂₉	C ₃₀	C ₃₁	C ₄₀	C ₄₁	C ₄₂	
Original value	800	0.9	0.75	0.8	3	0.85	0.75	0.9	

3.3 Compute the indicator weight

The risk evaluation indicator system of the tailings dam break involves three levels: target level, criterion level, and individual indicator level. The degree of influence of each level and each individual indicator on the risk level is also different. Analytic hierarchy process (AHP) developed by Saaty [26] has been ever favorable among multi-criteria decision-making methods, mainly due to its understandability in theory and the simplicity in application [27]. AHP has been deal with such hierarchy structure than can combine both quantitative (objective) and qualitative (subjective) indicators. Therefore, AHP method is applied to calculate the indicator weight of the tailings dam break, the specific steps are omitted, the results are shown in Table 3.

Table3. Calculation results of indicator weight

Individual indicator	Constant weight
(C ₁₀ , C ₁₁)	(0.201, 0.067)
(C ₂₀ , C ₂₁ , C ₂₂ , C ₂₃ , C ₂₄ , C ₂₅ , C ₂₆ , C ₂₇ , C ₂₈ , C ₂₉)	(0.013, 0.036, 0.017, 0.020, 0.005, 0.013, 0.005, 0.011, 0.004, 0.003)
(C ₃₀ , C ₃₁)	(0.049, 0.024)
(C ₄₀ , C ₄₁ , C ₄₂)	(0.287, 0.087, 0.158)

3.4 Calculate closeness and determine risk level

According to the established matter-element evaluation model, the distance of each indicator is calculated, as shown in Table 4. Then according to equations (2-7) to calculate the closeness of the object R_0 to each evaluation level.

$$P_1(R'_0) = 1 - \frac{1}{17 \times 18} \sum_{i=1}^n D_j(v'_i) \omega_i(X) = 0.9967$$

$$P_2(R'_0) = 1 - \frac{1}{17 \times 18} \sum_{i=1}^n D_j(v'_i) \omega_i(X) = 0.8579$$

$$P_3(R'_0) = 1 - \frac{1}{17 \times 18} \sum_{i=1}^n D_j(v'_i) \omega_i(X) = 0.5878$$

$$P_4(R'_0) = 1 - \frac{1}{17 \times 18} \sum_{i=1}^n D_j(v'_i) \omega_i(X) = 0.3328$$

After determining the closeness of the object R_0 towards each evaluation level, obviously, $P_1(R'_0) = \max\{P_j(R'_0)\} = 0.9967$. Then, according to equations (2-10), $j^* = 1.717 > 1.5$. Therefore, the risk level of the TSF is L_1 , the risk is relatively lower, and the degree of bias toward L_2 level is larger.

Table4. The distance value $D_j(v'_i)$ of the indicator for the tailings dam break

Individual indicator	$D_1(v'_i)$	$D_2(v'_i)$	$D_3(v'_i)$	$D_4(v'_i)$
C ₁₀	0	0	0.25	0.5
C ₁₁	-0.05	0.05	0.3	0.55
C ₂₀	0.54	0.76	1	1.23
C ₂₁	0	0.25	0.52	0.57
C ₂₂	0.25	0.32	0.7	1.07
C ₂₃	0	0	0.1	0.1
C ₂₄	0.15	-0.01	0.01	0.18
C ₂₅	-0.1	0.1	0.35	0.6
C ₂₆	0.05	-0.05	0.2	0.45
C ₂₇	4	4.19	4.37	4.56
C ₂₈	-0.1	0.15	0.4	0.65
C ₂₉	0	0	0.25	0.5
C ₃₀	0	0	0.45	0.75
C ₃₁	-0.29	0.29	0.4	0.5
C ₄₀	-0.1	0.1	0.35	0.6
C ₄₁	0	0	0.25	0.5
C ₄₂	-0.1	0.15	0.4	0.65

4 Conclusions

(1) In the paper, an improved extension matter-element model is applied and the grades of the TSF (first-fifth-class) is considered, a comprehensive risk evaluation model of the tailings dam break is finally established. By normalizing the classical field and the matter-element to be evaluated, and using the closeness principle to replace

the maximum membership criterion, the limitations and deficiencies of the traditional extension matter-element model in risk evaluation have been overcome.

(2) Using this model to evaluate the risk of Yujiaquan TSF, the result shows that its risk level is L_1 (lower risk), which is consistent with the actual operating situation.

(3) Indicators such as personnel qualification, daily management, and equipment monitoring and maintenance are worthy of much attention in the further safety management of the TSF and the tailings dam break.

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