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Evaluation Index System and Grading Standard for Major Hazard Source of Tailings Pond

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Abstract. It is to determine the evaluation index and grading standard of the major hazard sources of the tailings pond, so as to facilitate the risk classification management. According to the internal safety mechanism and relevant standards of the tailings pond, the evaluation index is divided into 3 levels. The system consists of 20 specific indicators, which are inherent risk indicators and affiliated risk indicators. In addition, the evaluation index method is used to quantify the grading standard through the evaluation matrix. Analysis results show that the indexes affecting the safety of tailings pond mainly include the hazard types of tailings pond, total capacity, dam height, safety degree, flood discharge system and seismic intensity.According to the comprehensive analysis method and the correlation degree analysis theory, the characteristic value and relative risk index of the evaluation index were quantified, and the results were all changed in 1~9. Based on the expert scoring method and the improved analytic hierarchy process, the weight of the 20 evaluation indexes for the overall hazard assessment of the tailings pond is determined. According to the evaluation index of each characteristic value of the evaluation index P, the major hazard sources of the tailings pond are divided into 4 levels. The results can provide a basis for enterprises to identify, classify and declare major hazard sources of tailings, and to provide the basis for the government's hierarchical supervision.

1. Introduction

Statistics show that as the end of 2017, there're about 10500 tailings ponds in China. Among them, the number of disease reservoirs is 4%, and the medium and large tailings ponds (dam height ≥ 30m) account for 20%. From 2007 to 2017, there were more than 80 accidents about tailings pond, and more than 350 people died and disappeared, which posed a serious threat to the safety of people's lives and property and the surrounding environment. In order to strengthen the supervision and management of major hazards and effectively prevent the occurrence of serious and extraordinary accidents, the former State Administration of Safety Supervision listed tailings pond as the scope of declaration of major hazards. However, the determination of hazard grade has not been explained in detail.

Therefore, according to the existing standards of tailings pond [1-2], through systematic safety analysis and evaluation methods, 20 major hazard classification indicators of tailings pond are determined. According to the result of expert scoring and the theory of analytic hierarchy process, the evaluation index and weight are determined. According to the evaluation index, the grade and classification criteria of major hazards in tailings pond are determined.

2. Evaluation Index System of Major Hazard Sources in Tailings Pond

2.1. Establishment of Evaluation Index System

The factors affecting the risk of tailings pond are diverse and complex. According to the principle of system, any system is composed of many subsystems and has a certain hierarchical structure [1].

Therefore, the construction process of index system follows the principle of "system cutting" in safety system engineering as a whole. That is to say, according to the separability of the analysis object and the criteria of its nature, function and structure, the system object is divided into types or situations. Firstly, the evaluation indicators are divided into two categories: intrinsic risk indicators and additional risk indicators. According to the source of risk, intrinsic risk indicators can be divided into two categories: intrinsic risk indicators of tailings pond itself and external intrinsic risk indicators. According to the nature, category and mode of action of risk indicators, the safety indicators which directly affect the safety of tailings ponds and other hidden danger indicators which indirectly affect the safety of tailings ponds are obtained by summarizing. Referring to the above analysis principles, combined with the standard [2-3], the above categories are subdivided layer by layer until the bottom of the independent elements. As shown in Figure 1.

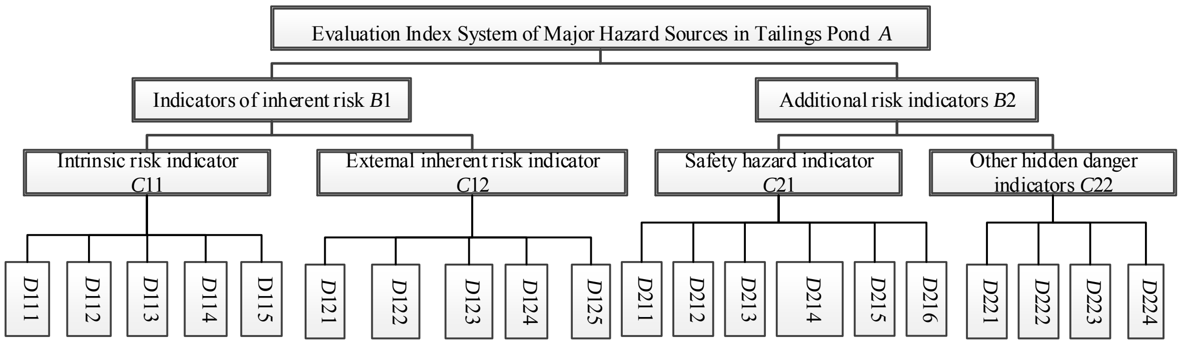

Figure 1. Evaluation index system of major hazard of tailing reservoir

Where, D111—Total storage capacity of tailings pond (V/10, 000 m^3); D112—Tailings dam height (H/m); D113—Hazard category of tailings pond;D114—Downstream slope ratio of initial dam (P); D115—The useful life of tailings pond (N/year); D121—Basic seismic intensity in dam site area; D121—Are there landslides and debris flows around the tailings pond;D121—Are reservoir areas in Karst or fissure-developed areas; D121—Average annual precipitation (R/mm/year);D121—Maximum daily precipitation (R_d/mm); D211—Safety classification of tailings pond; D212—Conformity of minimum dry beach length;D213—Minimum safety ultra high conformity;D214—Minimum depth conformity of saturation line downstream of accumulated dam; D215—Tailings dam integrity; D216—Seepage of tailings dam; D221—Flood control standard for tailings pond; D222—Drainage system integrity; D223—Integrity of tailings dam observation system; D224—Are there any external human factors affecting the safety of tailings pond in the reservoir area.

2.2. Eigenvalue analysis of evaluation indicators

The grade D index is obtained on the basis of the grade C index, and many factors are considered. Specifically, it includes the key monitoring indicators in design specifications and safety standards, and the main indicators affecting the safety of tailings ponds summarized from engineering design experience, etc. In order to ensure the validity and universality of the evaluation index, the relevant provisions of the existing tailings pond should be fully integrated when determining the D-level index.

The main provisions refer to are: classification method of tailings pond scale, safety degree of tailings pond, design requirement of dam structure, natural environment condition, seepage stability calculation scene, safety monitoring index of different grades, classification requirement of buried depth of saturation line, etc.

3. Classification of Major Hazard Sources in Tailings pond

3.1. Evaluation index

The evaluation index of major hazards in tailings pond is expressed as follows:

$$P=[A]\bullet[R] \tag{1}$$

Where, [A] is the relative risk index set of evaluation index. [R] is the weight set of evaluation index. The evaluation indexes in [A] are 20 indexes in Figure 1: D111~D115, D121~D125, D211~D216, D221~D224. The relative hazard index of various indicators is combined with the number of eigenvalues of indicators, and the average quantitative value is given according to the results of expert evaluation. They were divided into five groups: (1,9], [1,5,9], [1,7,9], [1,3.6,6.3,9], [1,3,5,7,9].

$[R] = [r_i]^T$, $i=1, 2, \ldots\ldots 20$, r_i is the weight of the first evaluation index.

3.2. Quantification of Eigenvalues of Evaluation Indicators

3.2.1. Quantitative methods and basic theories. At present, the quantitative methods of index eigenvalue are mainly divided into two categories: instrumental testing, mathematical statistics and other quantitative methods; confidence method, comprehensive analysis and other qualitative methods. The eigenvalues of the system evaluation indexes for major hazard sources in tailings ponds are highly ambiguous. Therefore, this study uses the fuzzy comprehensive analysis method [4], and determines the eigenvalues according to the expert evaluation results. For qualitative indicators, the eigenvalues given by expert reviews are dimensionless eigenvalues. The comprehensive analysis is as follows:

Suppose that the number of risk assessment indicators for a sub-index system is m. The set $U=\{u_1,u_2, \Lambda, u_i, \Lambda, u_m\}$. The number of experts involved in determining dimensionless eigenvalues of indicators is q. The set is $P=\{p_1,p_2, \Lambda, p_i, \Lambda, p_q\}$.

For index u_i, expert p_j gives an eigenvalue interval $[a_{ij},b_{ij}]$ based on its evaluation criteria and understanding of the index. Thus a set-valued statistical sequence is formed: (a_{i1},b_{i2}), Λ, (a_{ij},b_{ij}), Λ, (a_{iq},b_{iq}). Then the eigenvalue x_i of the evaluation index u_i can be calculated according to the following formula:

$$x_{\mathrm{i}} = \frac{1}{2}\sum_{j=1}^{q} w_j (b_{ij}^2 - a_{ij}^2) / \sum_{j=1}^{q} w_j (b_{ij} - a_{ij}) \tag{2}$$

In the formula, i=1,2,…,m; j=1,2,…,q; w_j denotes the eigenvalue of index j. With the help of the correlation degree analysis in fuzzy mathematics and grey system theory [5-6], the correlation degree between the assignment of experts and the eigenvalues of indicators obtained according to formula (2) can be determined.

$$\zeta_j = \frac{1}{m}\sum_{i=1}^{m} \frac{\min_j \min_i \Delta_{ij} + \rho \max_j \max_i \Delta_{ij}}{\Delta_{ij} + \rho \max_j \max_i \Delta_{ij}} \tag{3}$$

In the formula, $\Delta_{ij}=|x_i-u_{ij}|$, u_{ij} is a value in the upper, middle or lower limits of the interval$[a_{ij}, b_{ij}]$. ρ is the resolution coefficient, usually 0.5.

3.2.2. Quantitative results. Based on the above analysis of the major hazard assessment index and its eigenvalues of tailings pond, the quantitative results of each eigenvalue are obtained, as shown in Table 1.

Table 1. Quantitative results of characteristic value of rapid evaluation index

Level I Indicators	Level II Indicators	Level III Indicators	Eigenvalues of evaluation indicators and their relative risk indices				
*B*1	*C*11	*D*111	$V<10^2$	$10^2\leq V<10^3$	$10^3\leq V<10^4$	$V\geq 10^4$	—
		A_1	1	3.6	6.3	9	—
		*D*112	$H<30$	$30\leq H<60$	$60\leq H<100$	$H\geq 100$	—
		A_2	1	3.6	6.3	9	—
		*D*113	fourth kind category	third kind category	second kind category	first kind	—
		A_3	1	3.6	6.3	9	—
		*D*114	$P\leq 1:2.5$	$1:2.5< P\leq 1:2.0$	$1:2.0< P\leq 1:1.75$	$1:1.75< P\leq 1:1.6$	$P>$ 1:1.6
		A_4	1	3	5	7	9
		*D*115	$N<5$	$5\leq N<24$	$24\leq N<29$	$N\geq 30$	—
		A_5	1	3.6	6.3	9	—
	*C*12	*D*121	under Ⅴ	Ⅵ	Ⅶ	Ⅷ	above Ⅸ
		A_6	1	3	5	7	9
		*D*122	no	yes	—	—	—
		A_7	1	9	—	—	—
		*D*123	no	yes	—	—	—
		A_8	1	9	—	—	—
		*D*124	$R<400$	$400\leq R<650$	$650\leq R<900$	$900\leq R<$ 1150	$R\geq 1150$
		A_9	1	3	5	7	9
		*D*125	$R_d<50$	$50\leq R_d<70$	$70\leq R_d<90$	$90\leq R_d<$ 110	$R_d\geq 110$
		A_{10}	1	3	5	7	9
*B*2	*C*21	*D*211	normal	disease	danger	—	—
		A_{11}	1	7	9	—	—
		*D*212	$K\geq 1$	$0.8\leq K<1$	$K<0.8$	—	—
		A_{12}	1	7	9	—	—
		*D*213	$K\geq 1$	$0.8\leq K<1$	$K<0.8$	—	—
		A_{13}	1	7	9	—	—
		*D*214	$K\geq 1$	$0.8\leq K<1$	$K<0.8$	—	—
		A_{14}	1	7	9	—	—
		*D*215	very good	good	common	bad	—
		A_{15}	1	3.6	6.3	9	—
		*D*216	nothing	few	secondary	high	—
		A_{16}	1	3.6	6.3	9	—
	*C*22	*D*221	coincidence	inconformity	—	—	—
		A_{17}	1	9	—	—	—
		*D*222	good	common	bad	—	—
		A_{18}	1	5	9	—	—
		*D*223	complete	incomplete	nothing	—	—
		A_{19}	1	5	9	—	—
		*D*224	nothing	occasionally	often	—	—
		A_{20}	1	5	9	—	—

Note: D_{ijk} represents the evaluation index and A_i represents the relative risk index.

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3.3. *Weight of Evaluation Index*

Based on the analysis of evaluation indexes and their eigenvalues, and the latest weight determination methods, the improved analytic hierarchy process (IAHP) is used to determine the weight of 20 indexes. IAHP method is the mainstream method which can organize non-quantitative events hierarchically and synthesize people's subjective judgment to make thinking mathematically and quantitatively. It is suitable for this study.

3.3.1. *Index Weight Calculating Method.*

(1) Construct a comparison matrix, assuming that:

$$A_{ij}=\begin{cases}2,\text{Factor } i \text{ is more important than factor } j\\ 1,\text{Factor } i \text{ is as important as factor } j\\ 0,\text{Factor } j \text{ is more important than factor } i\end{cases} \tag{4}$$

Where, A_{ij} is the importance of the first factor i relative to the j factor. And if A_{ij} = 1, the comparison matrix is:

$$A=\begin{pmatrix}A_{11}\cdots A_{1n}\\ \vdots \quad \ddots \quad \vdots\\ A_{n1}\cdots A_{nn}\end{pmatrix} \tag{5}$$

(2) Calculating the importance ordinal number r_i:

$$\mathrm{r}_i=\sum_{j=1}^{n}A_{ij} \tag{6}$$

Where r_i is the sum of the elements in line i, $r_{max}=max(r_i)$, $r_{min}=min(r_i)$.
(3) Determine the judgment matrix:

$$B_{ij}=\begin{cases}\dfrac{r_i-r_j}{r_{\max}-r_{\min}}(k_m-1)+1 & r_i\geqslant \mathrm{r_j}\\ \left[\dfrac{r_j-r_i}{r_{\max}-r_{\min}}(k_m-1)+1\right]^{-1} & r_i\geqslant \mathrm{r_j}\end{cases} \tag{7}$$

Where, $k_m=r_{max}/ r_{min}$.
(4) To find the transfer matrix of the judgment matrix:

$$C_{ij}=\frac{1}{n}\sum_{k=1}^{n}\left(\lg\frac{b_{ik}}{b_{jk}}\right) \tag{8}$$

(5) Solving quasi-optimal consistent matrix of judgment matrix:

$$D_j=10^{Cij} \tag{9}$$

(6) The square root method is used to calculate the vector $\overline{W}$, and the weight vector is obtained by normalization. Specifically:

$$M_i = \prod_{j=1}^{n} d_{ij} \qquad (i = 1, 2, 3, \cdots, n) \tag{10}$$

Where, M_i is the opportunity of the elements in line i, and the root of the square is obtained as follows:

$$\overline{W}_i = \sqrt[n]{M_i} \tag{11}$$

Then, the vector $\overline{W}$=($\overline{W}_1$, $\overline{W}_2$, …$\overline{W}_n$)^T is normalized: $W_i = \overline{W}_i / \sum_{i=1}^{n} \overline{W}_i$. "$W$=($W_1$, W_2, …, W_n" is the weight vector. W=(W_1, W_2, …, W_n)

The accuracy of iteration calculation is 0.0001. The weights of 20 indicators can be obtained by substituting numerical calculation and ranking the evaluation indicators.

3.3.2. Index Weight Calculations. The weights of 20 evaluation indicators can be obtained by multiplying the weights of each factor at each level from top to bottom.

Table 2. Calculation results of weight of evaluation index

Index	Weight	Index	Weight
$D111(r_1)$	0.0958	$D211(r_{11})$	0.0905
$D112(r_2)$	0.0958	$D212(r_{12})$	0.0310
$D113(r_3)$	0.1582	$D213(r_{13})$	0.0310
$D114(r_4)$	0.0480	$D214(r_{14})$	0.0317
$D115(r_5)$	0.0320	$D215(r_{15})$	0.0484
$D121(r_6)$	0.0553	$D216(r_{16})$	0.0310
$D122(r_7)$	0.0296	$D221(r_{17})$	0.0208
$D123(r_8)$	0.0219	$D222(r_{18})$	0.0584
$D124(r_9)$	0.0296	$D223(r_{19})$	0.0208
$D125(r_{10})$	0.0362	$D224(r_{20})$	0.0340
The sum of weights of 20 evaluation indicators		1.0000	

3.4. Classification Standard for Major Hazard Sources in Tailings pond

According to the classification of relative hazard index of each characteristic value of evaluation index in Table 3, combined with the above IAHP analysis and expert evaluation results, the major hazard sources of tailings pond are divided into four levels, as shown in Table 5.

Table 3. Major hazard sources of tailings

Level	Level I	Level II	Level III	Level IV
Evaluation index P	P>7	5<P≤7	3<P≤5	P≤3

According to the actual operation conditions of tailings pond, 20 evaluation indexes and their relative hazard index in Table 3 were selected. Then multiply with the corresponding weight in Table 4. Finally, 20 passengers were added and compared with the P value of the evaluation index in Table 5. The major hazard grade of a tailings pond can be determined.

4. Conclusion

A clear and detailed classification method for major hazards in tailings pond is given in this paper. In practical application, only according to the actual operation of the tailings pond, by comparing the selection of evaluation index and corresponding risk index, after simple numerical calculation, the classification results can be determined after comparing with the classification standard given in Table 5. This method provides a basis for classified declaration and supervision of major dangerous sources in tailings ponds.

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