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Quantitative Assessment Method Study Based on Weakness Theory of Dam Failure Risks in Tailings Dam

MEI Guodong[a,b]a*

a China Academy of Safety Science & Technology, Beijing 100012, China
b University of Science and Technology Beijing, Beijing 100083, China

Abstract

Considering the current status of no quantitative assessment of dam failure risks in security assessment of tailings dam and that the fact of dam body being heterogeneous body isn't taken into account in stability calculation of the dam body, the article, based on assessment theory of weakness risks, puts forward the idea of viewing volume weight, internal friction angle and cohesion as random variables and adopting Monte-Carlo model to calculate effectiveness-losing probability of dam failure in tailings dam as well as establishing tailings flow model of tailings dam after dam failure based on hydrology, hydrodynamics and movement theory of non-Newtonian fluid to compute submergence range due to the failure; Loss ratio of dam failure in tailings dam is calculated through computation of loss of life, financial and environmental loss after dam failure. Finally, weakness level of dam failure in tailings dam is determined with the above data for improvement in security assessment technology of tailings dam and guarantee of safe and sound operation of tailings dam.

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Keywords: Tailings dam; dam failure probability; submergence range; loss rate; quantitative assessment

1. Introduction

Gangues produced by metallic and non-metallic domestic mining areas are estimated to be around 0.3 billion tons, which are basically piled up among 11946 tailings dams[1,2]. Highest height in those dams is

* Corresponding author. Tel.: +86-10-8491-1521; fax: +86-10-8491-1373.
E-mail address: meigd@139.com.

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260 m, with height of 26 dams exceeding 100 m, storage capacity of 10 dams exceeding 0.1 billion m^3. Dams whose height are less than 30 m take up 80% while gangues piled up in large and medium-sized dams take up 80% of the total tailings nationwide though the large and medium-sized dams only take 20% of total dams[3,4]. By the end of May, 2011, there are 2369 dams which are detected to be dangerous, risky, dilapidated and most of them are located in the upper reaches where are mostly densely populated [5,6], causing a huge potential safety hazard. Once dam failure happens, severe casualties and financial loss will be incurred. Since 2011, altogether 73 tailings dam accidents have happened, causing more than 500 deaths, with number of accidents and deaths on the rise year by year and resulting in a severe safety situation [7]. Among the accidents are 37 dam failure accidents which take up 57% of the total number and the death number taking up 98.6% of the total deaths. "9.8" extremely severe tailings dam failure accident happened on September 8, 2008 in Xiangfen, Shanxi released the following data: 190,000 m^3 flowing gangues, 2.5km flowing in length, 35.9 hectares of submergence, 281 deaths, RMB 96,192,100 Yuan in direct economic loss. The accident has caused extremely bad social influences [8].

Although enterprises are required to conduct a security assessment of tailings dam every 3 years as regulated in *Regulations on Supervision and Administration on Tailings Dam Safety* by State Administration of Coal Mine Safety in May, 2011, the assessment features low quality and limited methods, which are represented in the following:

(1) More qualitative assessment and less quantitative assessment. Assessment methods such as safety checklist analysis, preliminary hazard analysis and accident tree analysis are mostly adopted, which focus on experience of the evaluators and lack quantitative analysis and result of quantitative assessment.

(2) Excessive attention has been paid to the tailings dam while status of lower reaches of the tailings dam has been overlooked. Evaluation done on the tailings dam only focuses on filtration stability of tailings dam and dam body stability for calculation without taking account of residents living in lower reaches, number and distribution of equipment of heavy industries, thus causing the same tailings dam risk for sparsely-populated lower reaches and densely-populated lower reaches alike, which is greatly alienated from the actuality of risk assessment.

(3) Parameters chosen are all fixed values, with omission of sandwich or lenticular body spasmodically formed by withdrawal of ores in the piling-up dam of tailings dam.

Considering the insufficiency in security assessment of domestic tailings dam, the article, based on weakness risk assessment theory [9-13] and adopt Monte-Carlo module to calculate ineffectiveness probability of dam failure in tailings dam, with finite difference method to calculate submergence range due to dam failure and quantitative method to compute loss of life, financial and environmental loss after dam failure in tailings dam to finally determine weakness level of dam failure risk in tailings dam, therefore improving security assessment technology of tailings dam and guaranteeing safe and sound operation of tailings dam.

2. Basic Principles

2.1. Dam failure probability analysis

Dam failure probability analysis of tailings dam views stability analysis as a random procedure, taking factors influencing the stability such as intensity index c, value φ, and apparent density as the random measure, whose frequency distribution or distribution function will be given through tests and be determined relevant probable values in related interval accordingly.

Average value and variance of each parameter is computed by test data, followed by mathematic fitting analysis of cumulative distribution function. Random sampling of random variables whose distribution is known is conducted, followed by combination according to sequence of the random numbers to give a series of safety coefficient and draw the distribution curve. Dam failure probability refers to percentage of the total number of calculation of safety coefficients that are lower than 1.

$$P_f = \int_{-\infty}^{1} f(k)dk \tag{1}$$

In the equation: *f(k)*——probability density function of random variable *k*.

Monte-Carlo chooses the random number according to cumulative distribution function of random variable x_i to input into the analysis and derive a safety coefficient. As the input parameter is a random variable, the safety coefficient thus derived is a random variable too. Through the above repeated computation, the random sample representing safety coefficient will be given, based on which will make statistical nature calculation and fitting of distribution inspection available and finally give the dependability *RI* of stability in tailings dam and P_f the ineffectiveness probability.

Basic concept in Monte-Carlo for ineffectiveness probability in dam failure analysis is listed below:

(1) Set safety coefficient F_s of stability in tailings dam to function of n-numbered random variable as X_1、$X_2 \ldots X_n$:

$$F_s = g(X_1、X_2 \ldots X_n) \tag{2}$$

(2) Monte-Carlo method is applied to produce a series of random number as x_1 x_2, x_3….

(3) Transform the produced random number to derive the n'th random number x_{11}, x_{21}, x_{31}, …, x_{n1} of X_1、$X_2 \ldots X_n$.

(4) Solve the first value of F_s:

$$F_{s1} = g(X_{11}、X_{21} \ldots X_{n1}) \tag{3}$$

(5) Follow the above steps and conduct analogue for n-numbered times to derive n-numbered value as F_{s1}, F_{s2}, …F_{sn} of F_S.

It is a sample of F_s whose value is N. Compile statistics of samples when F_s is less than 1, namely the frequency *k*/N is no more than 1. It is the approximate value of P (F_s<1), namely the damaged probability whose side is less than 1:

$$RI(\text{normal}) = \frac{\mu_{F_s} - 1}{\sigma_{F_s}} \tag{5}$$

In the equation: *RI(normal)*——dependable index normally distributed;

μ_{F_s} ——average value;

σ_{F_s} ——average value;

When F_s is viewed as normal distribution of logarithm, equation (5) may be changed into

$$RI(\text{Lognormal}) = \frac{\ln\left[\dfrac{\mu_{F_s}}{\sqrt{1+V^2}}\right]}{\sqrt{\ln(1+V^2)}} \tag{6}$$

Among which:

$$V = \frac{\sigma_{F_s}}{\mu_{F_s}} \tag{7}$$

Ineffectiveness probability of tailings dam is:

$$P_f = 1 - \phi(RI) \tag{8}$$

2.2. Calculation method of submergence range in dam failure

Tailings flow model of tailings dam after dam failure is established based on hydrology, hydrodynamics and movement theory and calculation method of non-Newtonian fluid.

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=0 \tag{9}$$

Momentum equation:

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[(\mu+\mu_t)(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i})\right]+\rho B_i \tag{10}$$

k equation:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_i k)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}+G-\rho\varepsilon\right] \tag{11}$$

Equation:

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho u_i\varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}^{*}\rho\frac{\varepsilon^2}{k} \tag{12}$$

In the equation: ρ and μ refer to density and molecular viscosity coefficient; P refers to calibrated pressure; B_i refers to body force of unit volume while μ_t is the turbulence viscosity coefficient

2.3. Calculation method of loss level

Loss level (V) of submergence range in tailings dam may be constituted by weight method of multi-stress:

$$V= W_1H+W_2P_E+W_3S \tag{13}$$

In the equation, H、P、S has respectively represented loss of life, economic loss and influences on social environment and W_1、W_2、W_3 refer to weighting factor. Each loss value is calculated through the following equation:

$$\begin{cases} H=\sum_{i=1}^{n} N_i\times K_i \\ P_E=\sum_{t=1}^{m}\frac{A_t}{(1+j)^t} \\ W=N\cdot C\cdot I\cdot h\cdot H\cdot l\cdot L\cdot P \end{cases} \tag{14}$$

In the equation: i、N_i、k_i refer to sequence number that influences n'th residential places in the range of lower reaches of the tailings dam, residents number of the i'th residence, residents death rate in the i'th residence; t、A_t、m、j refer to period of benefit, anticipated benefit volume in the t'th period of benefit, annual benefit and discount rate; N、C、I、h、M、l、L、P respectively refers to endangered population coefficient, key city coefficient, key equipment coefficient, cultural relics coefficient, river way form coefficient, creatures habitat coefficient, human landscape coefficient and contaminated industry coefficient.

2.4. Calculation method of weakness level in dam failure risk

Weakness level is used to measure dam failure risk in tailings dam, which is defined as below:

$$R=P_f\times V \tag{15}$$

In the equation: R——weakness level of dam failure in tailings dam, 0~1.

3. Examples of Engineering Application

3.1. Engineering profile

The initial dam of a tailings dam is a water-permeable dam piled up with stones. The dam is 163.5m in level, with 14m in height and 5m in width and specific value in internal and external slope is 1:2.0. In the initial period, gangues are piled up above the 163.5m level. Five pack_ways with the respective height of 173.5m, 183.5m, 193.5m, 203.5m and 213.5m are arranged outside the dam, whose width are 5m and each specific value of slope section is 1:2.5. Now the pile-up has been 220m in level and the structure drawing is obtained through spot geologic drilling (refer to figure 1).

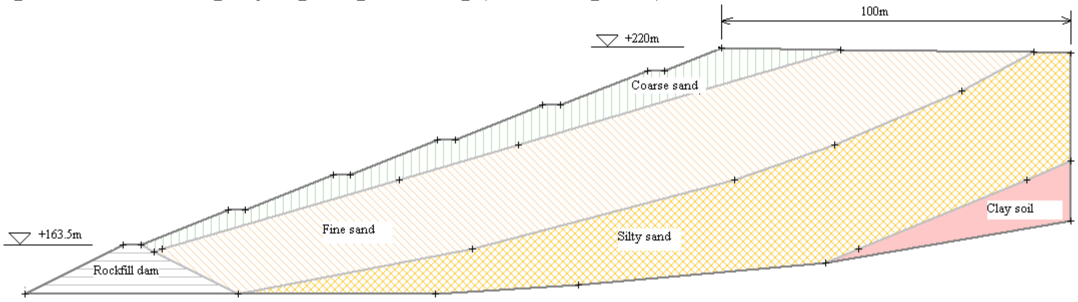

Figure 1 Structure of Tailings Dam

3.2. Physical mechanics parameters

According to experimental results of standard penetration, dynamic penetration test, spot density test, clay core test and permeable test, relevant physical mechanics parameters are obtained concerning the tailings dam; for details, refer to tables 1 and 2.

Table 1 Actual permeable coefficients in tailings dam

Permeable coefficient	Coarse sand	Fine sand	Silty sand	Clay soil
Horizontal permeable coefficient	3.6e-03	3.7e-03	2.0e-03	3.0e-06
Vertical permeable coefficient	6.4e-03	4.2e-03	9.5e-04	1.6e-05

Table 2 Actual physical mechanics parameters in tailings dam

Material name / Mechanics parameter		Coarse sand	Fine sand	Silty sand	Clay soil	Rockfill dam
Volume weight(kN/m3)	Average value	19	20	19.5	14.6	20
	Variance	1.1	0.8	0.9	2.8	0.6
	Max.	23.3	22.4	22.2	23	21.8
	Min.	15.7	17.6	16.8	6.2	18.2
Cohesion (kN/m2)	Average value	11	9.8	10.78	13.72	0
	Variance	1	1.8	1.9	2	0
	Max.	14	15.2	16.48	19.72	0
	Min.	8	4.4	5.08	7.72	0
Friction angle (deg)	Average value	32	29	28	26	38
	Variance	1.5	2.1	2.5	2.4	1
	Max.	36.5	35.3	35.5	33.2	41
	Min.	27.5	22.7	20.5	18.8	35

3.3. Calculation of dam failure probability

Ineffectiveness probability of dam failure in the tailings dam is 11.8% according to dam failure probability analysis, actual physical mechanics parameters and slide 5.0.

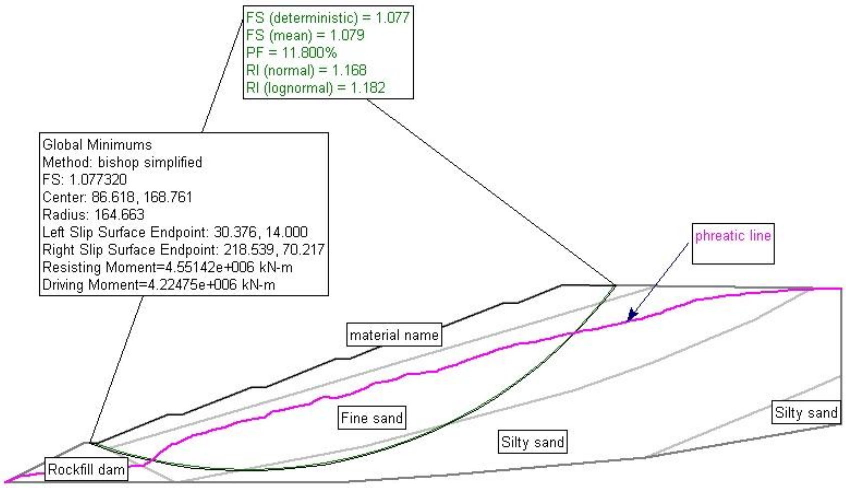

Figure 2 Calculation result figure of ineffectiveness of dam failure in tailings dam

3.4. Submergence range of dam failure and loss calculation

Submergence range of dam failure in the tailings dam is calculated by equations (9) through (12) with finite difference method to give submergence range and depth of dam failure as shown in figure 3.

Weight of each factor is derived through experts' evaluation and analytic hierarchy process: W1=0.45，W2=0.25，W3=0.3.

Loss of life, economic loss and environmental loss can be computed according to residential places, distribution status of industrial facilities in lower reaches of tailings dam.

Loss of life H=400×0.046+1200×0.04+800×0.045+100×0.1/100=1.124.

Economic loss PE=156870000/100000000=1.569.

Environmental loss W=0.6×0.7×0.8×0.9×0.9×0.8×0.7×0.8=1.02.

According to equation (14), loss level of submerged area due to dam failure of tailings dam can be calculated:

$$V=0.45\times1.124+0.25\times1.569+0.3\times1.02=93.5\%$$

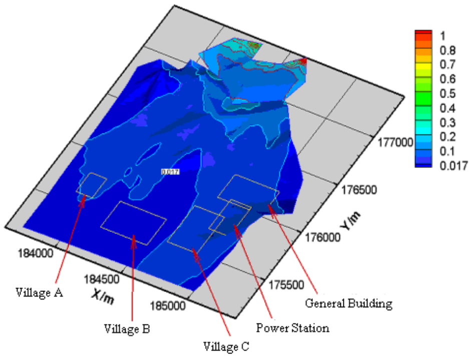

Figure 3 Submerged area of dam failure in tailings dam

3.5. Weakness level of dam failure risk of tailings dam

According to equation *(15)*, weakness level of dam failure risk of tailings dam is as follows:

$R=P_f\times V$=11.8%×93.5%=0.11

It is apparent that though the loss is huge in submerged area due to dam failure, due to small dam failure probability, the tailings dam risk is still tolerable.

4. Conclusion

Quantitative assessment method of weakness level calculation in dam failure of tailings dam is put forward by taking account of insufficient security assessment in tailings dam currently and assessment theory of weakness level with the following conclusions:

(1) Security assessment of tailings dam should adopt quantitative assessment method to specify risk level of dam failure in the tailings dam. Firstly, calculate the ineffectiveness probability of dam failure in the tailings dam and then compute loss level of submerged area based on the obtained data concerning submerged area and finally calculate the weakness level of dam failure in tailings dam based on ineffectiveness probability and loss level.

(2) Sandwich and lenticular body and heterogeneous body of the whole dam body are caused in the piling-up dam due to the ignorance of spasmodical piling-up procedure of tailings while geometrical parameter and physical parameter used in stability analysis of current tailings dam are fixed value. The idea is thus put forward to view volume weight, internal friction angle and cohesion as random variables and adopt Monte-Carlo principle to obtain ineffectiveness probability in dam failure of tailings dam through value analytical software.

(3) Tailings flow model of tailings dam after dam failure is established based on hydrology, hydrodynamics and movement theory of non-Newtonian fluid. Submerged area may be calculated through finite difference method or value analytical software.

(4) Risk loss of dam failure in tailings dam should include loss of life, property loss and environmental and resources loss. Besides, the risk loss should be weighted in a comprehensive manner to obtain the weakness level of dam failure risk in tailings dam.

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