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Research Article

Research on the Overtopping-Induced Breaching Mechanism of Tailings Dam and Its Numerical Simulation

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The centrifugal model test system is utilized to reappear the breaching process of a tailings dam. The results show that there are significant differences in breaching processes between tailings dams and earth-rockfill dams. Influenced by the special physical and mechanical properties of tailings, the breaching processes of tailings dams are of short duration, and the flood flow through the breach increase rapidly. Based on the centrifugal test results, considering the special physical and mechanical properties of tailings, a mathematical model for tailings dam breaching is established. In the model, the vertical undercutting and horizontal expansion are simulated utilizing the erosion rate formula which is derived from shear stress principle of water flow; limit equilibrium method is used to analyze the breach slope stability. In addition, the model adopts iterative calculation method to simulate the whole breaching process. The analysis results show that, the proposed model is applicable in modeling the dam breaching process for tailings dam due to overtopping.

1. Introduction

Tailings dams are the places for storing discarded tailings, which are usually formed by damming the valley. China owns the largest amount of tailings dams in the world. By the end of 2015, 8869 tailings dams were scattered all over China. Among these tailings dams, the number of upstream tailings dams is up to 1425 [1]. Compared to other kinds of tailings dams, the upstream tailings dam has the lowest safety factor [2, 3]. Through the statistical analysis of 3500 tailings dams worldwide, scholars found that breaching risk of tailings dams was more than 10 times that of earth-rockfill dams [4]. In recent years, extreme weather events and earthquake disasters occurred frequently, which increased the dam breaching probability of tailings dams. In 2000, the Baia Borsa gold mine tailings dam in Romania breaching caused by rainstorm and snowmelt, which released 100,000 cubic meters of tailings into the Lapus and Somes tributaries of the river Tisa, damaged the ecosystem, and killed aquatic lives [5]. In 2011, the Kayakari tailings dam in Japan breaching due to tailings liquefaction caused by earthquake, the discharged tailings destroyed many houses in the lower reaches [6]. In 2014, the Mount Polley mine tailings dam breaching due to dam foundation instability, about 4.5 million cubic meters of tailings flowed into Polley Lake and seriously polluted the environment [7]. Thus, once the tailings dam breaching occurs, it will seriously threaten the surrounding ecological environment and the safety of people's lives and property. To reduce consequences of the tailings dam breaching, many scholars have carried out studies on the breaching process of tailings dams and achieved some results [8–13]. However, these studies still use the research methods applied in earth-rockfill dams, which cannot accurately reflect the particularity of tailings dams. In addition, due to the lack of the simulation method agreed with the special physical and mechanical properties of tailings, the lose evaluation of tailings dam breaching and the proposal of emergency plan are short of reliable evidence. These weak points seriously restrict the advancement of disaster prevention and mitigation level of tailings dams. Therefore, it is necessary to study the breaching mechanism of tailings dams due to overtopping for revealing the failure law of them.

In this study, centrifugal model tests are conducted to reveal the breaching mechanism of tailings dam. Based on the centrifugal tests results, a mathematical model for tailings dam breaching is established, which can consider the special physical and mechanical properties of tailings. In the model, the vertical downcutting and lateral expansion are simulated utilizing the erosion rate formula derived from shear stress principle of water flow; limit equilibrium method is used to analyze the breach slope stability. In addition, the model adopts iterative calculation method to simulate the whole breaching process. The technical details are described in the following sections.

2. Centrifuge Model Tests of Tailings Dam Breaching

Since the breaching process of actual tailings dam is difficult to observe and reproduce [14], model test is an important way to study the breaching mechanism of tailings dams. According to the document retrieval results, now there is only a few small-scale flume model tests [15–19] preliminarily discussing the catastrophic mechanism of tailings dams. However, the difference between these models and actual tailings dams in the stress level is too large. Whether these models can reasonably reflect the breaching process of actual tailings dams is worthy of further study. Comparing with flume model tests, centrifugal model tests can improve the stress level of tailings dam models through changing centrifugal acceleration. Besides, centrifugal model tests can reappear the breaching process of tailings dam in short time [20]. Therefore, it is reasonable to study the breaching mechanism of tailings dam by centrifugal model tests.

2.1. Design and Manufacture of the Test Model. The test equipment consists of the following three parts: (1) 400 gt large geotechnical centrifuge, the maximum radius of the centrifuge is 5.5 m, the effective radius is 5.0 m, the maximum centrifugal acceleration is 200 g, and the effective load is 2 t. (2) Flow control system, the system is designed to adopt the idea of rotating water ring, which can provide an experimental flow of 0.01~0.05 m^3/s (prototype 100~500 m^3/s) at 100 times of gravity acceleration, with a duration up to 20 min (prototype 33.3 h). (3) Special test box integrated data and image acquisition system, the internal effective size of the test box is $1.2\,m \times 0.4\,m \times 0.8\,m$ (length × width × height). The integrated data and image acquisition system can capture and record the whole breaching process of the tailings dam under the condition of high centrifugal acceleration, the test equipment is shown in Figure 1. The working principle of centrifuge and the derivation of similarity criterion are referenced to related literature [21, 22]. For the centrifugal model test at N times of gravity acceleration, the similarity criterion of common physical quantities is shown in Table 1.

The physical and mechanical properties of tailings are obviously different from those of general cohesive soil and noncohesive soil [23]. As a kind of artificial soil, tailings have the characteristics of fine grain, low particle strength, and loose and large porosity [24, 25]. Therefore, the tailings from a surrounding tailings dam are chosen as dam construction materials for the centrifugal model tests. Considering the gradation feature of tailings, the tailings are sampled from

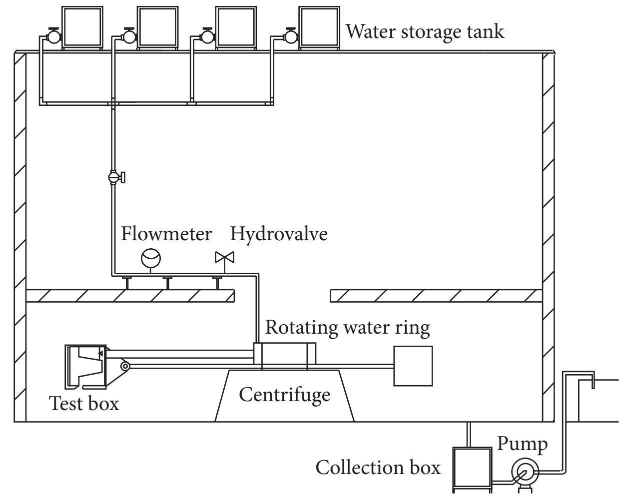

Figure 1: The centrifugal model test equipment for dam breaching.

different areas and depths of the tailings dam separately. Then, all the sampled tailings are mixed together, the density of mixture tailings is 2.08 g/cm^3, the water content is 16.5%, the specific gravity is 3.33, and the content of clay particles is 5%. In the centrifugal model tests, the gravity acceleration is set as 50 g, so the size ratio between model dam and prototype is 1 : 50. The height of model dam is 0.4 m and the width of dam crest is 0.3 m. Considering the storage capacity of actual tailings dam, the upstream reservoir is simulated by a water box with upper opening. The internal effective size of the water box is $0.2\,m \times 0.4\,m \times 0.5\,m$. In order to simulate the permeable boundary, the contact section between the water box and the dam is made of perforated plates (Figure 2). Since the complexity of the breaching mechanism of tailings dam, the centrifugal model tests were carried out two groups for different dam slopes. Taking one group as an example, in this test, the downstream slope ratio is 1 : 3.0, and the upstream inflow rate is $1.7 \times 10^{-3}\,m^3/s$. Limited by the size of model box, the tests are mainly aimed at the breaching section of tailings dam, so the downstream slope is cut off at the height of 0.2 m. The tailings dam model is shown in Figure 3.

2.2. Test Results and Analysis. According to the results of the tailings dam breaching tests, the breaching process can be divided into four stages, and the details are shown in Figures 4(a)–4(d). Stage 1: water flows over the crest of tailings dam and scours the dam body. Under erosion of the flow, many slender gullies are formed on the downstream slope of the tailings dam, as shown in Figure 4(a). Stage 2: the slender gullies on the right side of the downstream slope gradually expand and merge to form a breach channel. After the breach channel formed, the flow begins to discharge along it. At the end of this stage, a breach is formed in the right side of tailings dam crest, as shown in Figure 4(b). Stage 3: the breach continues to grow vertically and laterally. Since the flow in the breach channel is not cross the full section, erosion of the flow is concentrating on the lower region of the breach. With the breach growing in vertical direction, the

Table 1: Similarity criteria of common physical quantity in centrifugal model tests.

Physical quantity	Acceleration	Length	Area	Volume	Normal stress	Sheer stress	Strain	Void ratio	Flow	Mass	Viscosity	Force	Time	Density
Similarity ratio	N	$1/N$	$1/N^2$	$1/N^3$	1	1	1	1	$1/N^2$	$1/N^3$	1	$1/N^2$	$1/N$	1

Figure 2: The water box.

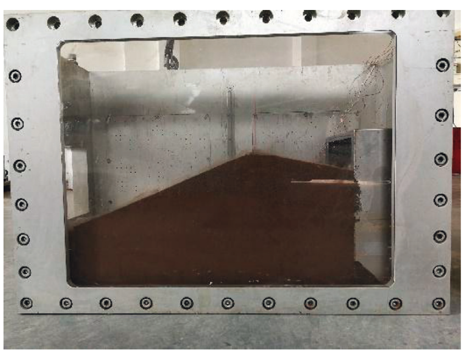

Figure 3: Tailings dam model.

breach side-slope angle continues to increase and finally results in the breach collapsing. In this stage, the discharge flow increases gradually and reaches its peak, as shown in Figure 4(c). Stage 4: growth of the breach gradually slows down until stops. At the end of this stage, when the bed shear stress in the breach is smaller than critical stress required to initiate detachment for the material, the breach erosion stops. After the dam breaching stopping, the final breach is shown in Figure 4(d).

To simplify the calculation, the measured parameters are converted into the corresponding numerical values under the constant gravity condition according to the centrifugal acceleration. Therefore, the upstream inflow rate is 4.25 m^3/s, the peak flow through the breach is 21.88 m^3/s, the time to peak flow is 0.13 h after dam breaching, and the breaching time is 2.56 h (Figure 5). The final breach has an inverted trapezoidal cross section, the depth is 15.6 m, the top width is 9.0 m, and the bottom width is 5.0 m (Figure 6).

3. Numerical Model

From the above test results, it can be clearly seen that surface erosion is the main erosion mode in the breaching process of tailings dam. The development process of the breach is mainly composed of "continuous vertical downcutting and lateral expansion caused by flow erosion" and "intermittent lateral large expansion caused by collapse of the breach slope." In both tests, the breach increases very rapidly, and the breach flow quickly reaches the peak. However, the investigation of tailings dam accidents [26, 27] show that there are the same situation in actual tailings dam breaching. The breach growth mainly depends on the erodibility of the dam material. Therefore, the special physical and mechanical properties of tailings should be fully considered when establishing a mathematical model for tailings dam breaching.

3.1. Water Balance Relationship. As described above, tailings dams are different from earth-rockfill dams, and they are used for storing discarded tailings. Tailings pumped into upstream reservoir in the form of slurry, so there are not only tailings but also water storing in the reservoir. Due to sedimentation of particles, water is mainly distributed in the upper layer of the reservoir. In the breaching process of the tailings dam, the water level in the upstream reservoir is a dynamic process. The volume change of water in the reservoir is equal to the difference between inflow and outflow, so the water balance can be described by

$$A_s \frac{dz_s}{dt} = Q_{in} - Q - Q_{spill}, \tag{1}$$

where t is time, z_s is water level of reservoir, A_s is surface area of reservoir, Q_{in} is inflow, Q is breach flow, and Q_{spill} is flow through dam crest.

Another important factor affecting the change of reservoir water level is the geometric characteristic of reservoir. The reservoir geometric characteristic can be represented by the storage capacity curve. The curve is usually given as pair values of surface area and water level in the reservoir. In some cases, only the reservoir area information or the reservoir capacity information is known, and the storage capacity curve is not available. When this occurs, the storage capacity curve can be calculated by the formula proposed by Wu [28]:

$$A_s = \alpha_r h^{m_r}, \tag{2}$$

where α_r and m_r are coefficients, and the value of m_r generally ranges from 1.0 to 3.0, and h is water depth in the reservoir. When the water depth and the corresponding reservoir area or reservoir capacity are known, the coefficients α_r and m_r can be calculated by formula (2). If only the reservoir area or the reservoir capacity is known, m_r is assumed to be 2.0 [28], then other related parameters can also be calculated by formula (2).

(a) (b) (c) (d)

Figure 4: The breaching process of the tailings dam model.

3.2. Breach Flow Routing. Based on the results of above tests, it is known that the breach formed in tailings dam breaching usually has an inverted trapezoidal cross section. Therefore, the breach flow can be calculated by the formula of the broad-crested weir:

$$Q = k_{sm}\left(c_1 bh^{1.5} + c_2 mh^{2.5}\right), \quad (3)$$

where b is the bottom width of the breach; m is the slope ratio of the breach slope (horizontal/vertical); c_1 and c_2 are both corrected coefficients, refer to the research of Singh [29], $c_1 = 1.7$ and $c_2 = 1.3$; and k_{sm} is submergence corrected coefficient for tailwater effects on weir outflow, which can be calculated by the formula proposed by Fread [30] and Singh [29].

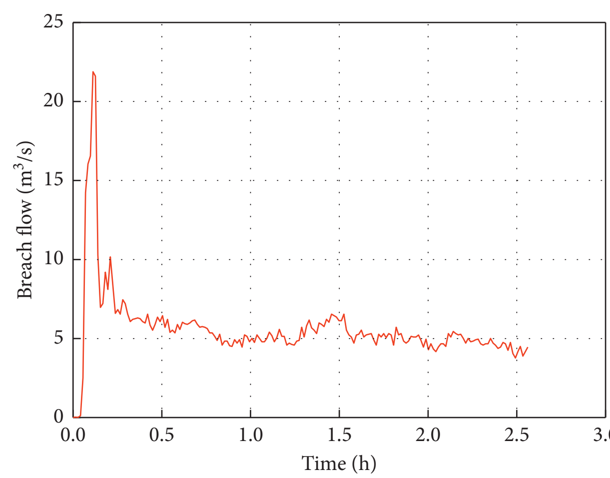

Figure 5: The breach flow hydrograph.

3.3. Dam Breaching Process. A simplified method is used to simulate the erosion process of the breach, which assumes the breach having a flat bottom. The erosion at the bottom section of the breach is calculated through the formula proposed by USDA-NRCS [31]:

$$\frac{dz_b}{dt} = k_d\left(\tau_b - \tau_c\right), \quad (4)$$

where (dz_b/dt) is erosion rate of the breach bottom; k_d is erosion coefficient; τ_b is bed shear stress; and τ_c is critical shear stress of the dam material. The erosion coefficient k_d can be measured by tests [32, 33] or calculated using the empirical formula proposed by Temple and Hanson [34]:

$$k_d = \frac{5.66\gamma_w}{\gamma_d}\exp\left[-0.121c\%^{0.406}\left(\frac{\gamma_d}{\gamma_w}\right)^{3.1}\right], \quad (5)$$

where γ_w is specific weight of water; γ_d is dry specific weight of the dam material; and $c\%$ is clay content of the dam material. By considering water content, clay content, and dry density of the tailings, the formula can reasonably reflect the effect of the physical and mechanical properties of tailings on

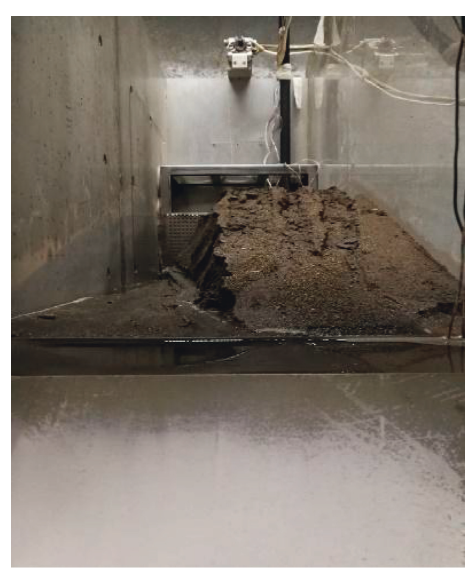

Figure 6: The shape of final breach.

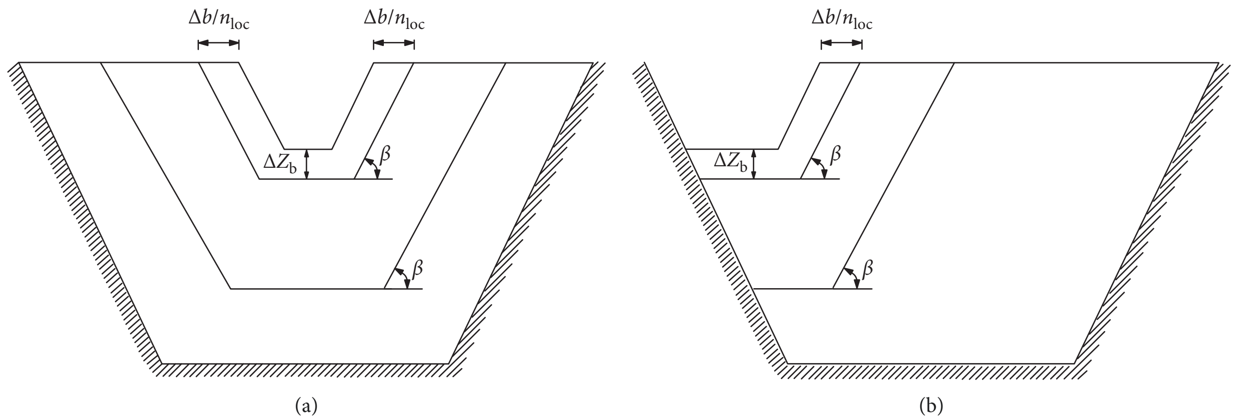

Figure 7: The sketch of erosion of breach. (a) $n_{loc} = 2$. (b) $n_{loc} = 1$.

the dam breaching process. τ_b can be calculated using Manning's formula:

$$\tau_b = \frac{\rho g n^2 Q^2}{A^2 R^{1/3}}, \tag{6}$$

where A is the cross-sectional area of the breach flow; R is the hydraulic radius; ρ is the density of the water-tailing mixtures, $\rho = \rho_w (1 - C_t) + \rho_d C_t$; C_t is the volume concentration of tailings in mixtures; and n is Manning's roughness coefficient. The volume change of the breach ΔV consists of two parts: the change of the breach bottom elevation Δz_b and the change of the breach width Δb (Figure 7). It is assumed the relationship between Δz_b and Δb is determined by

$$\Delta b = \frac{n_{loc} \Delta z_b}{\sin \beta}, \tag{7}$$

where β is slope angle of the breach and n_{loc} is erosion mode of the breach and $n_{loc} = 1$ for one-sided erosion and $n_{loc} = 2$ for both-sided erosion.

Through the centrifugal model tests of tailings dam breaching, it can be found that the development process of the breach mainly consists of the vertical downcutting process and the lateral expansion process. Besides erosion of the discharge flow, the breach collapsing is another main factor resulting in lateral expansion of the breach. As described above, erosion of the flow is concentrating on lower region of the breach. With the process of erosion, the breach side-slope angle gradually increases. When the angle exceeds the critical value, the sliding force of the soil is greater than that of the sliding resistance. At this point, landslide or collapse of the breach slope makes the breach width increasing suddenly. In this model, limit equilibrium method is used in the analysis of side-slope stability (Figure 8).

In Figure 8, the sliding surface in the breach slope is assumed as a plane, so the angle between the sliding surface and the bottom is α. Then, in order to further simplify the analysis of side-slope stability, the influence of resistance at both ends of the sliding soil mass is neglected. F_d is sliding force, which reflects the component of gravity of the soil on the sliding surface, and can be calculated using the following formula:

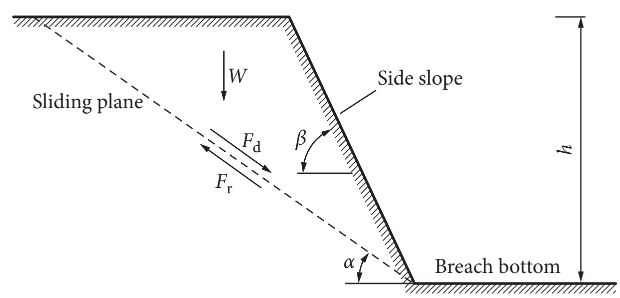

Figure 8: Analysis of side-slope stability.

$$F_d = W \sin \alpha = \frac{1}{2} \gamma_s h^2 \left(\frac{1}{\tan \alpha} - \frac{1}{\tan \beta} \right) \sin \alpha, \tag{8}$$

where W is gravity of the tailings on the sliding surface; γ_s is specific weight of the tailings; and F_r is sliding resistance consists of frictional resistance and cohesion, which can be calculated using the following formula:

$$\begin{aligned} F_r &= W \cos \alpha \tan \varphi + \frac{ch}{\sin \alpha} \\ &= \frac{1}{2} \gamma_s h^2 \left(\frac{1}{\tan \alpha} - \frac{1}{\tan \beta} \right) \cos \alpha \tan \varphi + \frac{ch}{\sin \alpha}, \end{aligned} \tag{9}$$

where φ is the internal friction angle of the tailings and c is the cohesion of the tailings. When $F_r < F_d$, sliding occurs in the breach slope.

3.4. Algorithm of the Numerical Model. To simulate the discharge flow and breach development at each time step, the iterative method of time steps is used in the tailings dam breaching simulation. Figure 9 shows the flow chart of the numerical method. In Figure 9, input files include initial conditions, boundary conditions, and calculation parameters. After setting the time step Δt, the breach flow Q, the change of water level of reservoir Δz_s, the change of the breach bottom elevation Δz_b, and the change of the breach width Δb in the first time step can be calculated through initial conditions. Therefore, in the next time step, the water level of reservoir is $z_s - \Delta z_s$, the breach bottom elevation is $z_b - \Delta z_b$, and the breach width is $b - \Delta b$. Then, checking the breach slope stability, if $F_r < F_d$, sliding occurring in the breach slope and calculating Q, Δz_s, Δz_b, and Δb, if not, going to the next time step. Before the calculation of the next time step, checking the values of τ_t and τ_0, if $\tau_t > \tau_0$, starting the calculation; if $\tau_t < \tau_0$, ending the calculation and outputting Q, z_s, z_b, and b of current time step. The procedure of the tailings dam breaching is listed as follows (Figure 9).

4. Numerical Model Verification

To verify the rationality of the proposed model, the centrifugal model tests of tailings dam breaching are selected. In two tests, the downstream slope ratios are 1 : 3.0 and 1 : 4.0, other parameters such as properties of the tailings, geometric characteristics of the dam, and reservoir characteristics are shown in Table 2.

The comparison of calculated results and measured data is shown in Table 3, including the peak breach flow Q_p, the breach width B and b, and the time to peak flow t_p. The comparisons of the calculated breach flow hydrographs and measured ones are shown in Figure 10, and the evolution of the breach widths are shown in Figure 11.

Case 1. The downstream slope ratio is 1 : 3.0. The initial breach was formed at the dam crest at 0.06 h; then the flow begins to discharge along the breach. Since erosion of the flow concentrated on the breach, the breach grows quickly. In addition, the upstream reservoir has a less storage, which results in the breach flow reaching the peak quickly. The peak breach flow calculated using the numerical model is 23.21 m^3/s, and the time to peak flow is 0.124 h after dam breaching. At the end of dam breaching, the top width of the final breach is 9.21 m, and the bottom width is 4.83 m. Comparing to the measured data, the peak breach flow calculated using the numerical model has increased by 6.07%, the time to peak flow has decreased by 4.62%, the top width of the final breach has increased by 2.33%, and the bottom width of the final breach has increased by 3.4% (Table 2). From Figures 10(a) and 11(a), it can be seen that the calculated breach flow hydrographs and final breach are almost in accordance with the measured ones.

Case 2. The downstream slope ratio is 1 : 4.0. The initial breach was formed at the dam crest at 0.08 h; then with the fast growth of the breach, the breach flow reaches a peak quickly. The peak breach flow calculated using the numerical model is 19.64 m^3/s, and the time to peak flow is 0.149 h after dam breaching. At the end of dam breaching, the top width of the final breach is 9.78 m, and the bottom width is 4.46 m. Comparing to the measured data, the peak breach flow calculated using the numerical model has increased by 2.99%, the time to peak flow has increased by 6.43%, the top width of the final breach has increased by 5.16%, and the bottom width of the final breach has decreased by 3.04% (Table 2). From Figures 10(b) and 11(b), it can be seen that the calculated breach flow hydrographs and final breach are almost in accordance with the measured ones.

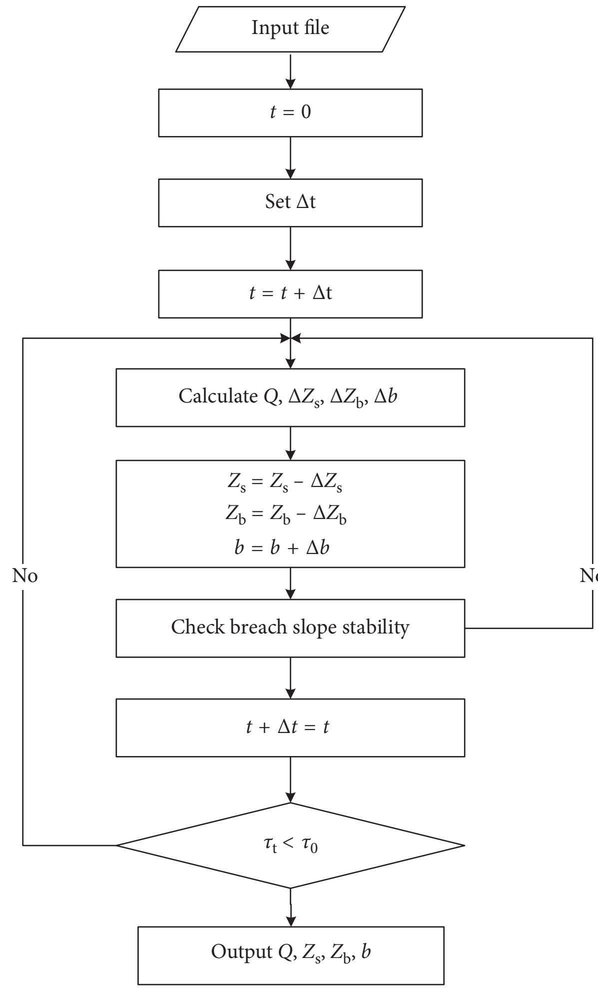

Figure 9: The flow chart of the numerical method.

Through the analysis of the two cases, it is proved that the proposed model is applicable in modeling the tailings dam breaching due to overtopping.

In order to analyze the influence of tailings properties on the discharge process of breach flow, an earth-rockfill dam breaching model [35] is selected to simulate the cases mentioned above. The selected model is a typical physical-based model, which cannot fully consider the special physical and mechanical properties of tailings. The comparison of the breach flow hydrographs calculated by two models are shown in Figure 12, and the comparison of the results calculated by two models and measured data is shown in Table 4.

Table 4 shows that the time to peak flow predicted by the selected model in two cases has larger errors, but the peak breach flow and the predicted final breach widths are close to the measured ones. When the tailings properties are not considered, the breach flow increases slowly and the time to the peak flow is much later than that of the proposed model (Figure 12). Therefore, the earth-rockfill dam breaching model cannot simulate the breaching process of the tailings dam rationally.

Table 2: Calculation parameters of tailings dam breaching process.

Tailings density (kg/m^3)	Dam height (m)	Crest width (m)	Inflow (m^3/s)	Dam length (m)	Upstream slope ratio	Reservoir storage (m^3)	Manning' coefficient	d_{50} (mm)	Porosity	Cohesion (kPa)	$\tan\varphi$	Upstream water level (m)	Downstream water level (m)
2080	20	15	1.7×10^{-3}	15	0.1	3.25×10^{3}	0.020	0.168	0.47	13.3	0.56	19.9	0

Table 3: Comparison between the calculated results and the measured results.

	Measured data				Calculated results			
	Q_p (m^3/s)	B (m)	b (m)	t_p (h)	Q_p (m^3/s)	B (m)	b (m)	t_p (h)
Case 1	21.88	9.0	5.0	0.13	23.21	9.21	4.83	0.124
Case 2	19.07	9.3	4.6	0.14	19.64	9.78	4.46	0.149

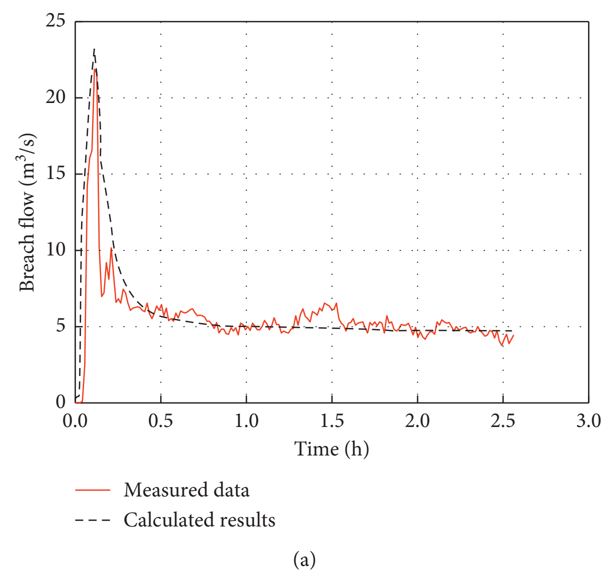

Figure 10: The comparisons of the calculated and measured breach flow hydrographs. (a) Case 1 (b) case 2.

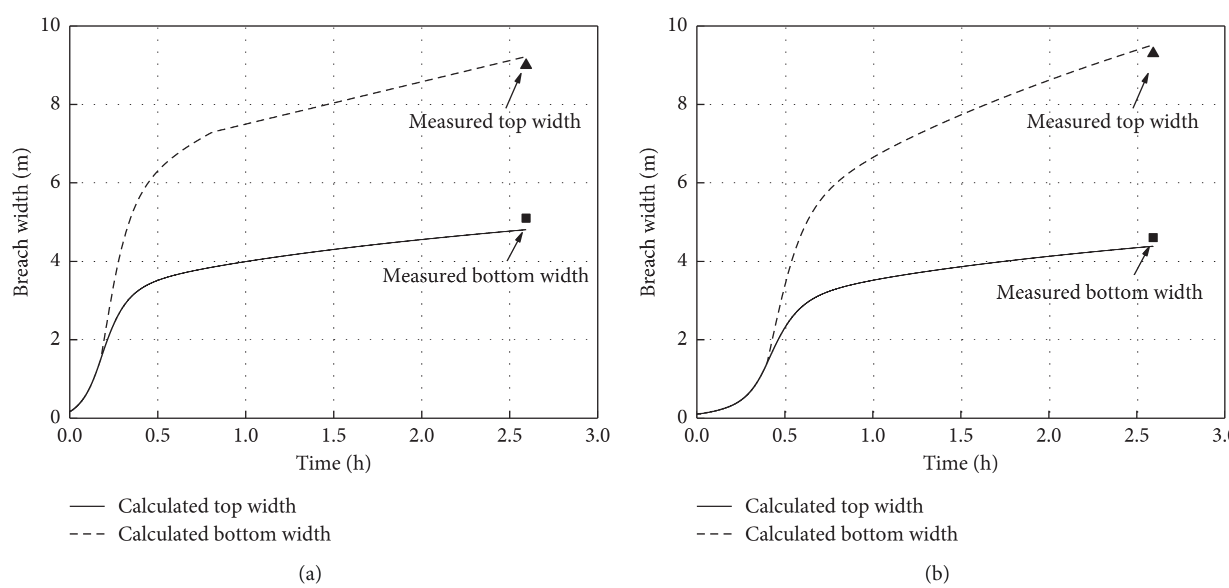

Figure 11: The evolution of the breach widths. (a) Case 1 (b) case 2.

5. Conclusions

In this paper, the centrifugal model tests are conducted to study the breaching mechanism of tailings dam. From the model tests, it is found that the breaching process of tailings dam can be divided into four stages: Stage 1, erosion on the dam slope; Stage 2, downcutting of the breach; Stage 3, erosion on the breach slope; and Stage 4, the breach collapsing. Affected by the tailings properties and reservoir characteristics, the breaching process of tailings dam is obviously different from that of earth-rockfill dam. The tailings dam breaching has a short duration, and the breach flow increases rapidly. Based on the centrifugal test results, a mathematical model for tailings dam breaching is

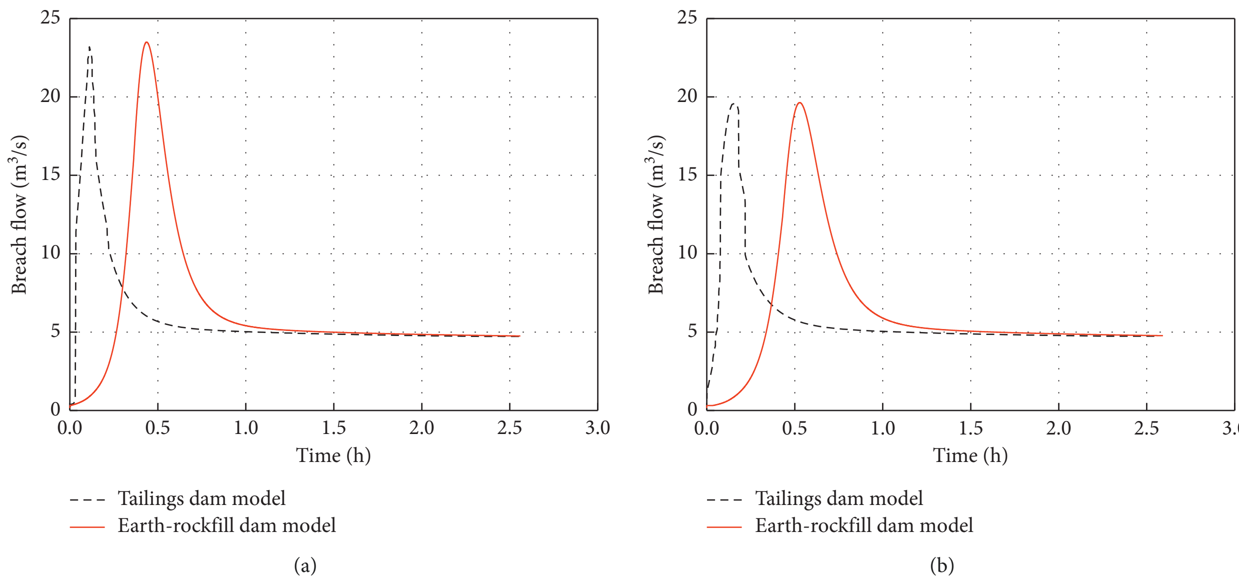

FIGURE 12: The comparisons of the breach flow hydrographs calculated using two numerical models. (a) Case 1 (b) case 2.

TABLE 4: Comparison of results simulated by two models.

	Calculated results											
	The proposed model				The selected model				Measured data			
	Q_p (m^3/s)	B (m)	b (m)	t_p (h)	Q_p (m^3/s)	B (m)	b (m)	t_p (h)	Q_p (m^3/s)	B (m)	b (m)	t_p (h)
Case 1	23.21	9.21	4.83	0.124	23.49	9.21	4.83	0.437	23.21	9.21	4.83	0.124
Case 2	19.64	9.78	4.46	0.149	19.82	9.47	4.26	0.496	19.64	9.78	4.46	0.149

established, which can consider the special physical and mechanical properties of tailings. In the model, the vertical downcutting and horizontal expansion are simulated using the erosion rate formula which is derived from shear stress principle of water flow; limit equilibrium method is used to analyze the breach slope stability. In addition, the model adopts iterative calculation method to simulate the whole breaching process. To verify the rationality of the proposed model, the centrifugal model tests of tailings dam breaching are selected. The analysis results show that the peak flow, the time to peak flow, and the width of the breach calculated by the proposed model have small errors; the calculated breach flow hydrographs are almost in accordance with the measured ones. Therefore, the proposed model is applicable in modeling the dam breaching process for tailings dam due to overtopping.

Data Availability

The numerical calculation data used to support the findings of this study are included within the article; the chart data used to support the findings of this study are included within the supplementary information file.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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Supplementary Materials

The supplementary materials include centrifugal test results and calculation results of numerical model. In the supplementary material file, t is the time, q is the breach flow, b is the bottom width of the breach, and B is the top width of the breach. Measured data are the centrifugal test results, and calculated data are the calculation results of numerical model. (*Supplementary Materials*)

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