Model Test Study on Dam Failure in Tailings Pond

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Abstract. This paper establishes the physical model of the prototype tailings pond using the similarity theory by taking a heightened and expanded project of tailings reservoir in Chengde, Hebei Province as an example and studies the process and mechanism of partial failure of the tailings reservoir when the drainage system fails by adopting the model test of the dam failure. The result shows that the dam damage can be divided into three categories: soil flow damage, gully damage and collapse damage. In addition, this paper analyzes the reasons for the three categories of damages.

1. Overview

The dam failure in tailings reservoir usually happens suddenly because of different reasons, but often with a signal. For example, failure of the drainage system will result in shorter drywall lengths and many cracks would emerge before the dam becomes unstable [1]. Risk analysis of tailings pond is of great significance to prevent dam failure.

Scholars at home and abroad have conducted extensive research on the stability and failure mechanism of the tailings reservoir [2]. For example, Qi Qinglan and Zhang Liting [3-4] have proposed a new method for generalizing the three-dimensional numerical model for the tailings reservoir with complex terrain and put forward specific measures to reduce the saturation line. Huang Qingfu [5] has introduced BIM technology into stability analysis, dam failure numerical model establishment, dam numerical simulation and post-processing of tailings reservoir and has established an integrated numerical simulation system for dam failure in tailings reservoir based on BIM technology. Hughes [6] has proposed the evaluation method of dam stability and summarized the successful experience of managing tailings pond by studying its safety management and the stability of the dam body. Shakesby et al. [7] have analyzed the development and characteristics of the dam failure by exploring the factors leading to dam break in the Arcturus gold mine in Zambia.
Present studies focus little on physical model test of tailings ponds, which is because the construction of a complete tailings pond model requires a large space and higher demand for simulating complex terrain. This paper takes an actual project as an example and studies the local failure process of the tailings reservoir caused by the drainage failure, describes the failure phenomenon, and analyzes the failure mode, damage type, and damage mechanism by adopting a physical model of the tailings pond established by a self-developed model test platform of dam break.

2. Overview of prototype tailings pond

The tailings pond in Chengde, Hebei Province is a valley-type tailings pond with the top elevation of about 777.1 m and the total dam height of about 74.1 m. The average slope ratio of fill dams above 759.5 m is about 1:3.8. A horizontal dam face drainage ditch is arranged on the 759.5 m and 770.0 m elevation platforms, a longitudinal drainage ditch is arranged on the dam face, and a dam shoulder drainage groove is arranged on both sides of the dam body. Manual and on-line monitoring facilities, including displacement monitoring and saturation line monitoring, are installed on the dam face, as shown in Figure 1.

The final elevation after the heightening of tailings pond is 833.0 m, with the total dam height of 130.0 m. Its total storage capacity is 13.831 million m$^3$, making it a second-class reservoir. Taking into consideration the space utilization, dam stability, and topographical conditions, a 60 m wide counter-pressure platform is reserved at the top elevation for slowing down the outer slope ratio of the fill dam and use waste rock to apply pressure on the slope.

Though the particle size analysis and physical and mechanical index test of the sand in prototype tailings pond, the following data is obtained: the density of tailing sand particle $\rho_p = 2.56$ g/cm$^3$, dry density $\rho_d = 1.77$ g/cm$^3$, median diameter $d_{50} = 0.150$ mm, effective internal friction angle $\phi' = 28.5^\circ$ and effective cohesion $c' = 8.0$ kPa.

3. Model test

3.1. Building the model dam body

Some text. The length of the scale $\lambda_L = 90$ is set according to the size of the site. The similarity relationship between the physical quantities is derived according to the Bockingham $\pi$ theorem while ensuring similar stability and safety conditions between the model and the prototype, as shown in Table 1. Since the debris flow model test needs to be conducted later, the selected model sand should also be similar to the prototype in settlement, sand carrying ability, and starting.
Table 1 Physical model scale of dam body failure

| Model scale | Geometric scale | Particle weight | Safety coefficient | Gravity acceleration | Internal friction angle | Cohesion |
|-------------|----------------|-----------------|-------------------|----------------------|------------------------|----------|
| Expression  | $\lambda_L = \frac{L_p}{L_M}$ | $\lambda_P = \frac{P_p}{P_M}$ | $\lambda_F = \frac{F_p}{F_M} = 1$ | $\lambda_g = \frac{g_p}{g_M} = 1$ | $\lambda_\phi = \frac{\phi_p}{\phi_M} = 1$ | $\lambda_c = \lambda_L^2 \lambda_P$ |

Note: $\lambda$ is the scale, P subscript is for the prototype value, and M subscript is for the model value.

(1) Model sand selection

Based on the basic parameters of the prototype tailing sand, this test takes the coal ash at 35 m of the ash discharge of Huaneng Shang’an Power Plant for the physical property test. Result shows that the coal ash, composed of glass beads, is light gray with moderate particle density and grade and chemical stability. Before the test, the ash gradation test of the coal ash is first carried out according to the requirements of the Standard for Geotechnical Test Method (GB/T 50123-1999), and the result is shown in Figure 2. The median diameter of the soil particle is 0.055 mm.

By testing the shear index and physical and mechanical properties of coal ash, the following data is gained: particle density of coal ash $\rho_s = 2.17 \text{ g/cm}^3$, dry density $\rho_d = 1.08 \text{ g/cm}^3$, cohesion $c = 0.08 \text{ kPa}$, internal friction angle $\phi = 28^\circ$. From the test data of the prototype sand and coal ash, the following data can be obtained: $\lambda_p = \rho_d / \rho_M = 1.18$, $\lambda_\phi = \phi_p / \phi_M = 1.02$, $\lambda_c = c_p / c_M = 100$, which basically meet the scale relationship ($\lambda_p = 1$, $\lambda_\phi = \lambda_L$, $\lambda_c = \lambda_L^2 \lambda_P$) listed in Table 1. In addition, the median diameter is similar in starting conditions [8].

(2) Model establishment

Build the dam body on the top of the model tailings pond. The geotextile filter layer in the prototype is replaced by filter paper. The inner and outer slope ratio of the model and the prototype are the same. Based on the similar scale of the model, the initial 25 cm high model dam uses fine-grained stones while the outer slope is compressed by coarse-grained stones. The average slope ratio of the waste rock compression is about 1:3 while the total height of the model fill dam is 1.41 m, as shown in Figure 3.

Figure 2. Grading curve of coal ash

Figure 3. Dam completion

Figure 4. Dam conditions at 28h27min

Figure 5. Dam conditions at 28h32min
3.2. Analysis of dam failure process

After the establishment of the model dam, the water supply system controls the water flow, maintains the normal water level, and begins to infiltrate the dam. This stage continues until there is water seepage at the foot of the initial dam slope, lasting for nearly 20 hours.

When infiltration is completed and the dam body forms a normal seepage line, the dam break model test officially begins. At this time, the water level in the reservoir is set and maintained relatively higher (to simulate the operating state of drainage failure of the tailings reservoir). Meantime, the water is continuously injected into the deposited beach. At 9 h, the amount of water seepage at the foot of the initial dam was significantly increased, and the local dam face and the counter-pressure platform of the pile dam began to wet.

At 9 h 24 min, the water seepage started and gradually increased in the vicinity of the midpoint of the pile dam on the counter-pressure platform, which was about 10 cm wide. As the seeping water increases and becomes turbid, accompanied by fluid and soil destruction, the seeping water accumulated on the platform and then flew down the slope of the fill dam. Due to water gravity of the water flow and sand carrying effect, the first fine gully was gradually formed on the slope surface of the fill dam. At 9 h 27 min, due to the increase of accumulated water on the platform, a second fine gully began to form at about 10 cm to the left of the first gully and gradually went downward. At that time, the first gully arrived at the junction of the fill dam and the initial dam and has formed a fine gully network, as shown in Figure 4.

At 9 h 32 min, the seepage area increased and the fine gully continued to extend downward to form a small scarp. At the same time, water continued to flow out of the joint between the left side of the counter-pressure platform and the slope of the fill dam. At that point, the surface of the counter-pressure platform has been completely wetted and swamped with local subsidence, as shown in Figure 5.

At 9 h 43 min, the continuous erosion of the gully caused by water seepage made first gully wider and deeper, gradually forming a small scarp with ups and downs [9-11] and becoming the mainstream while the second fine gully stopped developing. The middle part of the initial dam is covered by the model sand brought out by the soil flow, and the mud at the foot of the initial dam started to go downward. At 10 h 14 min, at the upper part of the gully, or the junction between the counter-pressure platform and the fill dam, a vacant area begins to form due to water erosion and soil flow. A large area of the counter-pressure platform was covered by water. The third fine gully was formed near the left side of the mountain, as shown in Figure 6.

At 11 h 26 min, soil flow damage reached into the dam body with obviously settled counter-pressure platform and enlarged cracks, resulting in the first soil collapse in the outer area, as shown in Figure 8. At this time, the third fine gully also developed into a small scarp. At 11 h 55 min, multiple soil collapse occurred, as shown in Figure 9.
4. Mode and failure mechanism analysis of dam body failure

When the drainage facility of the tailings reservoir fails, there are many reasons for and forms of dam failure. Influenced by various factors, each stage has different forms of failure, which can be divided into three categories: soil flow damage, gully damage and collapse damage, which are different but connected.

4.1. Soil flow damage

Soil flow is a phenomenon in which the soil or soil particles are simultaneously suspended and moved because of the seeping water flows out of the surface of the local area. It occurs in any type of soil when the hydraulic gradient reaches the threshold. The collapsing stage of this test begins with the occurrence of soil flow damage in the dam body.

After the infiltration is completed, the dam body maintains a high water level and continuously raises the saturation line. Water escaped at the junction of the second stage of the fill dam and the counter-pressure platform with soil flow. At the same time, the water washed the face of the fill dam downstream, which is similar to the flooding phenomenon. However, due to the slow development of the early stage of saturation, the water flow is small, making its combined damage different from flooding.

As soil flow damage intensifies, the soil gradually lost its support, causing local collapse. After that, the soil flow damage continued. It was observed that the silt sand has covered the initial dam, as shown in Figure 12.
When the upward permeability of the soil in the dam body overcomes the downward gravity, the soil body will float or be damaged. The hydraulic gradient at the critical state of the soil flow is the critical hydraulic gradient of the soil:

\[ i_{cr} = \frac{G_s - 1}{1 + e} = (G_s - 1)(1 + n) \]

\( G_s \) is the specific gravity of the soil; \( e \) is the void ratio of the soil; \( n \) is the porosity of the soil.

It can be seen that the critical hydraulic gradient of soil flow damage depends on the physical properties of the soil itself. The tailing sand is mostly composed of fine-grained particles, whose specific gravity is generally 2.5~2.7 t/m³ with porosity generally between 0.8 and 1 and the void ratio between 0.44 and 0.5. So, the critical hydraulic gradient of tailing sand is between 0.85 and 0.95. Therefore, in actual practice, attention should be paid to the critical hydraulic gradient to prevent soil flow. As for the heightened and expanded tailings pond, the dam slope is relatively gentle with smaller cross section at the foot of the slope. In order to enhance the stability of the fill dam, counter-pressure platform is often used to reduce the possibility of shearing and slipping [12].

4.2. Gully damage
In actual dam breaking, the development of the gully can be roughly divided into four stages based on its degree and shape: the fine gully stage, the cutting gully stage, the gulch stage, and the resting stage.

The development of gully in this model test can be applied to the above four stages. After the water flew through the counter-pressure platform to the first section of fill dam, the fine stage begins; then it developed to the main gully to form the cutting gully, which was gradually developed to form the gulch and continued to get wider; finally, it stabilized.

4.3. Collapse damage
As the soil flow gradually developed inside the dam, the sand inside the dam slope was rushed to the downstream while the upper dam is suspended above the flowing soil. At this time, a crack started to form at the junction between the counter-pressure platform and the first stage of the fill dam. As the crack expanded, the collapsed body sloped towards the valley and continued to suffer erosion after it fell into the valley, resulting in large-scale failure and the formation of the failure body.

5. Conclusion
This paper reveals three forms of local damage of the dam body, including soil flow damage, gully damage, and collapse damage by taking the real tailings reservoir as an example and adopting the model test to study the process and mechanism of dam failure caused by the failure of drainage system. The hydraulic gradient reaching the critical value is the condition for the soil flow to occur while the critical hydraulic gradient is closely related to the nature of the soil itself. The soil flow damage is the root cause of the whole dam failure, therefore, it should be protected in design, construction and monitoring. The gully damage is the scouring damage on the dame slope caused by shearing effect of the water. First, a gully net is formed, but with the continuous erosion of water, the surface erosion quickly evolves into gully erosion. Test result shows that the development of the gully lays the foundation for the dam failure. The collapsing stage in this test is mainly in the form of falling. Since the interior of the dam is eroded, the upper soil is subjected to tensile force, leading to cracks. The downstream soil accumulated with erosion. The above are all directly related to the final dam failure. In the collapsing stage, the failure volume rapidly increases, making it the most dangerous stage during the dam failure.

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