Research on the Model Test of the Debris Landslide’s Evolution Process in Tailings Reservoir

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Abstract. Based on the actual tailings reservoir project, a model test study on the evolution pattern of dam-breaking debris landslide is carried out. According to the similarity criterion of water flow and mud-sand movement, coal dust satisfying the similar relationship is selected as model sand. By analyzing the dam-breaking debris landslide’s range, propulsion speed, submerged depth distribution and particle deposition characteristics, the movement pattern of the landslide is obtained. In the short time after the dam break, the submergence range and advancing speed of the debris landslide increase rapidly. During the propulsion process, due to the increase of the debris landslide in the downstream of the valley, the debris landslide is diffused and the energy consumption during the flow is made. The advancing speed decrease until the landslide stops; The final submerged depth distribution of the dam breach has obvious randomness and non-uniformity, which is mainly related to the downstream terrain; According to the particle size grading analysis of the soil sample at the characteristic location, the further away from the dam toe, the finer particle content in the debris landslide.

1. Overview

The tailings dam is a kind of artificial dam with high potential energy, and it is also a major hazard source for mining industry [1]. China's tailings dams are built on the mountain, and there are many residential areas, farmland, rivers and important building facilities and traffic routes downstream. Once the tailings dam breaks down, it will not only cause great economic losses, but also threaten the safety of people's lives and property. Since the beginning of the 20th century, there have been more than 200 types of tailings accidents [2]. At present, domestic and foreign scholars' research on tailings dams mainly focuses on the seepage characteristics and stability of dams. There are few studies on the movement characteristics and evolution patterns of debris landslide in tailings reservoirs. The movement mechanism of tailings dam breach and debris landslide is complex, involving hydraulics, soil mechanics, hydrology, geology and sediment movement mechanics. At present, the research on tailings dam breach and debris landslide is still in its infancy [3].

Based on the actual tailings reservoir project, this paper conducts a model test study on the evolution pattern of dam-breaking debris landslide, and establishes a test platform for the tailings
reservoir dam-breaking debris landslide model. According to the similarity criterion of water flow and the mud-sand movement, coal dust is selected as model sand. In the model test of dam breach and debris landslide, the motion pattern of dam breach and debris landslide is obtained by analyzing the submerged extent, propulsion speed and submerged depth distribution of dam breach.

2. Overview of the prototype and model of tailings dams
Located in a tailings dam in Chengde City, Hebei Province, the initial dam of the tailings reservoir is a permeable rock-filled dam. The height of the initial dam of the tailings reservoir is 626.0 m, the dam crest elevation is 638.0 m, and the initial dam slope ratio is 1:1.8, the average slope ratio of the outer slope is 1:2. Two layers of 500g/m² geotextile are provided as the filter layer on the upstream slope and the bottom of the initial dam. The average slope ratio of the outer slope of the tailings reservoir accumulation dam is 1:4 (the actual average slope ratio of the piled dam is 1:1.87), and the final stacking elevation of the design is 676.6 m (the tailings accumulation level has reached 676.3m when the dam breaks), and the tailings reservoir’s total storage capacity is about 400,000 m³, which belongs to the fourth-class reservoir. The drainage solutions of the tailings reservoir adopt the pre-buried horizontal drainage pipe facilities. An east-west road passes 20m downstream of the tailings reservoir, and the north side of the road is adjacent to a factory. There is a river 130m downstream. At 530m downstream, it is a natural village with about dozens of households.

![Figure 1. Model test platform](image)

After considering the engineering requirements, laboratory site and facilities, etc., the geometrical (length) scale of the model, the corresponding flow rate scale and roughness ratio are determined. According to the prototype topography, the prototype roughness is about 0.028. The roughness rate is similar so that the model roughness is required to be 0.015. The roughness of the cement surface is about 0.014–0.017, and the model test bench is covered with cement mortar to meet the similar requirements of roughness. The model test platform includes a model water quantity control system, a tailings reservoir dam platform, a downstream debris flow evolution area, and a recovery system, as shown in Figure 1.

3. The selection of model sand
The flow of debris landslide in the tailings reservoir is mainly affected by gravity. The movement of the water flow is similarly designed according to gravity similarity and resistance; the movement of muddy sand is similarly designed according to settlement and meets similar startup.
According to the relevant regulations[4-5], the particle composition analysis of the prototype tailings sand samples was carried out in three groups. The median diameter \(d_{50}\) of the three groups of tailings sands are 0.125 mm, 0.145 mm, 0.120 mm, and the average value was 0.130 mm. The tailings sand gradation of the group tailings is relatively good, and the tailings sand particle size grading curve is shown in Fig. 2. According to the classification specification of tailings facilities (GB50863-2013), all the samples are tail silt. The physical properties test and shear test were carried out on the three groups of sand samples, and the average values of each characteristic index were obtained: density \(\rho = 2.03\), particle density \(\rho_s = 2.72\), water content rate \(\omega = 14.93\%\), dry density \(\rho_d = 1.77\), saturation density \(\rho_{sat} = 2.12\), saturation \(S_r = 75.56\%\), void ratio \(e = 0.54\), cohesion \(\tau = 6.5\) kPa, internal friction angle \(\varphi = 32.3\°\), median diameter \(d_{50,r} = 0.130\) mm.

The choice of model sand is the key factor for the correct simulation of the movement pattern of the dam-breaking debris landslide in the prototype tailings reservoir. In the dam-breaking debris landslide model test, the research object is not the trajectory of a single tailings particle in the water, but the influence of accumulated particles. Therefore, the whole tailings sand is taken as the research object. According to the similar conditions of the model sand proposed by Zhang Hongwu [6], the coal dust which has good similarity with the physical and mechanical properties of the prototype sand is selected as the model sand. The particle size ratio \(\lambda_d = \frac{\lambda_{\gamma'}}{\lambda_y} = 2.01\), satisfied the settlement similarity of the prototype sand and the model sand. The median diameter is used as the standard for model sand selection. The median diameter of the prototype sand is \(d_{50,r} = 0.130\) mm, and the average median diameter of the model coal dust is \(d_{50,m} = 0.065\) mm.
The starting flow rate of the model sand is determined by the indoor tank test. The starting flow rate of the model sand is within the range of 0.06 to 0.14 m/s within a certain model water depth. The starting flow rate of the prototype sand is calculated to be between 0.40 and 0.47 m/s [7], which is closer to the flow rate scale of mud sand movement. Therefore, the model sand is similar to the mud sand movement.

The author's previous research results show that [8], the entire dam body's fracture zone is in the middle of the dam's outer slope, and extends from the top of the dam to the junction of the initial dam and the accumulation dam. As shown in Figure 3.

4. Model test

In the following, the evolution pattern of the dam-breaking debris landslide will be analyzed from the aspects of the submerged extent, propulsion speed, submergence depth and particle deposition pattern of the dam-breaking debris landslide. The given values have been converted into prototype data according to the model scale. From the dam body collapse of the tailings reservoir to the end of the dam-breaking debris landslide evolution, the whole process lasts for 180 s, and the dam-breaking debris landslide volume is $6.43 \times 10^4$ m$^3$.

4.1. Flooding range Propulsion speed

Figure 4 shows the downstream submergence range of the typical dam-breaking debris slide. Figure 5 is a schematic diagram of the submerged range and thickness at the final moment. Figure 6 shows the relationship between the drowning range of the dam-breaking debris landslide and time.

The debris landslide movement process can be divided into three stages according to its submerged range change pattern:

The first stage is the rapid increase stage of the dam-breaking debris landslide inundation range, which is 42 s after the dam break. At $T=42$ s, the average distance from the front of the debris landslide to the dam toe is 264.61 m, and the submerged range is $14800$ m$^2$. At this stage, the tailings sand with huge gravitational potential energy is transformed into muddy fluid with larger kinetic energy in a short time, and the cross section of the gully is small, the recharge volume of the debris landslide is sufficient, and the submerged range is increased rapidly.

The second stage occurs within 42-90 s after the formation of the dam-breaking debris landslide. This stage is the stage of steady growth of the submerged range. At $T=90$ s, the average distance from the landslide’s front to the dam toe is 331.33 m, and the submerged range is 23 800 m$^2$. At this stage, due to the increase of the cross-flow cross section downstream of the valley, the debris landslide is diffused, and the downstream slope of the valley is reduced and the debris landslide replenishment in the reservoir area is insufficient and the energy consumption during the landslide process makes the debris landslide’s propulsion speed gradually decrease, and the submergence range increases gradually.

The third stage is from $T=90$ s to the end of evolution at $T=180$ s, and the debris landslide slowly evolves. At $T=180$ s, the front peak of the debris landslide advances to 386.75 m from the dam toe, and the final submerged range is about 29 400 m$^2$. At this stage, the upstream debris landslide replenishment is insufficient, the debris landslide propulsion section continues to increase, and the energy consumption during the flow process is further reduced by the slope. All these factors contribute to the deposition of the dam-breaking debris landslide. The deposition is stable until the movement is over.
4.2. Propulsion speed

Figure 7 is a plot of the peak forward velocity of the debris landslide as a function of time. Figure 8 is a plot of the propulsion distance as a function of time. Here, the propulsion distance refers to the curve distance of the movement path of the dam break debris landslide from the dam toe.

The front peak propulsion speed of the dam-breaking debris landslide can be divided into three stages according to its changing pattern.

The first stage is within 18s after the dam break. At this stage, the front peak thrust velocity increases rapidly, reaching the peak of the propulsion speed at T=18 s, which is about 11.46 m/s, and the front peak propulsion distance is about 111.60 m. At this stage, the tailings sand with high potential energy advances to the downstream gully of the initial dam under the impact of water flow, and rapidly forms a debris landslide. Due to the small cross section of the valley and the large longitudinal slope, it provides favorable conditions for the debris landslide to convert from the gravitational potential energy to the kinetic energy.

In the second stage, T=18s to T=60 s, the peak forward velocity of the dam-breaking debris landslide decreases rapidly. At T=60s, the debris landslide propulsion speed has been reduced to 1.56 m/s and the front peak propulsion distance is approximately 299.85 m. At this stage, the dam-breaking debris landslide rushed out of the valley, the cross-flow section increased, the longitudinal slope slowed down, and the energy loss during the flow, which led to a rapid decrease in the dam-breaking debris landslide propulsion speed.

In the third stage, T=60s to T=180 s. At this stage, the peak velocity of the debris landslide slowly decreases. At T=180s, the peak velocity of the debris landslide has decreased to 0.15 m/s, and most of the debris landslide has stopped.

4.3. Submergence depth analysis

Figure 9 shows the final submerged depth distribution of the dam-breaking debris landslide. The final submerged depth distribution of the dam-debris debris landslide shows obvious randomness and non-
uniformity. At the beginning of the dam break, the water rushed out of the valley with the collapsed dam. After rushing out of the valley, as the slope of the terrain gradually decreases, the collapsed dam of the larger diameter finally accumulated in the left front of the gully, 95m from the dam toe. So, the depth of the submerged area is deep; In the central part of the submerged area, the submerged slope has little change, so the submergence depth is relatively uniform; the accumulation pattern from the far side of the dam toe is related to the slow flow of the debris landslide. As the debris landslide velocity further reduced, the sedimentation effect is obvious. Eventually a thin stack with thick edges forms in the middle.

4.4. analysis of particle deposition characteristics
In order to explore the sedimentary characteristics of the dam-breaking debris landslide, after the dam-breaking debris landslide evolution is completed, seven characteristic points (shown in Figure 10) are selected along the dam-breaking debris flow evolution path, particle analysis test is carried out on the debris fluid at the characteristic point. The larger particles (greater than 0.075 mm) were analyzed by sieve analysis, and the smaller particles (less than 0.075 mm) under the sieve were analyzed by pipetting method.

After drying the soil samples of each characteristic point, 200g of each of them is subjected to a screening test. After the screening test is completed, fine-grained soil samples under the sieve are taken, and a pipette test is performed to analyze the particle size of the fine particles. The sand particle size gradation accumulation curve is shown in Figure 11. The results show that as the sampling feature points are further from the dam toe, the grain composition of the sand sample shows that the content of the coarse particle gradually decreases, while the content of fine particle gradually increases.

5. Conclusion
In this paper, the actual tailings pond engineering is taken as an example to carry out the model test of the tailings dam breach and debris landslide. The main conclusions are as follows:
The change of the submerged range of the dam-breaking debris landslide can be divided into three stages: in the first stage, the tailings sand with large gravitational potential energy is converted into muddy fluid with larger kinetic energy in a short time, and the gully flow cross section is small, the debris landslide is sufficient, the submergence range is increasing rapidly; in the second stage, due to the increase of the overflow section in the downstream of the valley, the debris landslide is diffused. At the same time, the downstream slope of the valley is reduced, the debris landslide in the reservoir area is insufficient, and the energy consumption during the flow process makes the propulsion speed of the debris landslide gradually decrease and the submerged range grows more stable. In the third stage, due to the continued increase of the debris landslide propulsion section, the energy consumption during the flow process and the terrain with the decreasing slope, the deposition of the dam-breaking debris landslide is beneficial, and the deposition is stable and the movement is over.

The change of propulsion speed can be divided into three stages. In the first stage, the propulsion speed of the dam-breaking debris landslide increases rapidly, the propulsion speed of the second stage decreases rapidly, and the propulsion speed of the third stage decreases slowly.

The final submerged depth distribution of the dam-breaking debris landslide shows obvious randomness and non-uniformity.

According to the particle size grading analysis of the soil samples at the characteristic locations, as the position is further from the dam toe, the content of fine particles in the debris landslide increases and the content of coarse particles decreases.

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