Tailings Dam Flood Overtopping Failure Evolution Pattern

Enji SUN\textsuperscript{a,b}, Xingkai ZHANG\textsuperscript{b}, Zhongxue LI\textsuperscript{b}, Yunhai WANG\textsuperscript{a}, a*  
\textsuperscript{a}Mining Safety Technology Institute of China Academy of Safety Science and Technology, Beijing, 100012, China  
\textsuperscript{b}University of Science and Technology Beijing, Beijing, 100083, China

Abstract
To analyze the tailings dam failure evolution pattern, a tailings dam overtopping evolution model was studied based on the physical model experiment method. Based on a non-constant unsaturated flow and sediment erosion mechanism of non-equilibrium theory, the model similarity theory and dam breach erosion model, using the tailings which was from tailings dam as the research object, the tailings dam overtopping breach evolution pattern was investigated on an outside independently developed tailings dam break simulation platform. The results show that the dam displacements are depended on the dam saturation degree during tailings dam flood overtopping failure. The higher saturation lines are, the larger sliding displacements are. The dam failure extent is related with the overflow breach erosion. In this experimental condition, the dam displacements, saturation line height, the maximum flow and the dam break evolutions were presented. Decreasing the saturation line height, increasing the dry beach length, setting up dam surface drainage channels and other measures can help reduce the tailings dam flood overtopping failure disaster damage.

Keywords: tailings dam; overtopping; dam failure; break evolution; breach erosion model

1. Introduction
Tailings dams are important facilities in the mining production operation. The safety is not only related to mine production and construction normally, but also related to the people’s lives safety downstream the dam and the surrounding environment [1]. Potentially tailings dam failure is disastrous and causes high-energy mudslide swept downstream [2]. Generally the tailings dam collapse and burst damage possibility is widespread higher, most of which are caused due to flood overtopping [3]. Therefore, the research on...
the tailings dam flood overtopping failure assists the dam disaster prevention and provides important scientific reference value.

The domestic and foreign scholars have studied the tailings dam collapse mechanisms and stability by the methods of theoretical calculation, numerical simulation and model experiment, etc. [4-7]. Till now, tailings dam failure researches are studied from the theoretical analysis and field investigation and physical model experiments mainly focus on the tailings dam slope stability [8-12]. There are few literatures about the tailings dam overtopping evolution by using physical model experiments and no systemic special studies on the downstream transmission mechanism of flood and mudslides caused by the tailings dam failure and the corresponding mathematics, physics simulation and physical simulation.

This research gave out detailed study on the tailings dam flood overtopping failure and its evolution by outdoor physical model experiment based on the unsteady flow and sediment erosion unsaturated nonequilibrium mechanism. According to the model similar theory and outburst erosion model principles, the tailings dam flood overtopping failure process was simulated and the evolution model was established. The results provide guidance for the stability control and safety work under flood conditions. It contributes important guiding significance and scientific support in the recognition of the tailings dam failure flood overtopping mechanism.

2. Tailings dam failure physical model

2.1. Model prototype

Tailings dam flood overtopping failure model prototype is a tailings dam in China, which is located at the valley in the North 0.7km away the mill. This tailings dam is permeable rock-fill dam. The West dam bottom elevations is 149.3m, the East dam bottom elevation is 143.5m. The dams crest width is 5m. The inner and outer slope ratio is 1:2.0. The ultimate crest elevation is 163.5m. The total tailing dam storage capacity is about 13.5 million m³ and it designed service life is 20 years.

The mainly research contents of tailings dam flood overtopping failure physical model experiment are:
- Study the dam displacement regulation under flood conditions while the water level is rising;
- Monitor the saturated lines accumulation variation while the flood coming into the dam;
- Explore the process and development of the dam flood overtopping failure and collapse;

In accordance with the tailings design materials, considering the most failure areas occurred near the outer slope dam foundation. This physical model experiment only simulates the tailings dam for the 180-220m elevation, which is the most tailings dam flood overtopping failure happened area. The main parameters of the dam are: height is 40m, dam max length is 400m, outer slope ratio 1:2.0, inner slope ratio is 1:6.0, and the beach length is 120m. According to the model similar theory, the scale model of the tailings dam flood overtopping experiment is 1:100. The size of the model is 400 cm × 40 cm × 20 cm (length × width × height). The dry beach length is 1.2 m, outer slope ratio is 1:2.0, and inner the slope ratio is 1:6.0.

2.2. Model experiment platform

To simulate the tailings dam flood overtopping failure and collapse process, an outdoor experiment simulation platform was built in Shunyi District, Beijing. The platform includes flood control area, the model building area, erosion platform, cut-off ditch, water control system, backwater system, water storage systems. Flood control area and model building areas is 4 m × 4 m × 2 m (length × width × height) three-dimensional space, which ensure the physical model building and the anti-seepage effect after the water are pumped into the dam. The erosion platform is 10m × 4m × 0.4m (length × width × height),
which is used to study the accumulation of sediment downstream and tailings transport rules, and alleviates the impact of destructive dam failure flood. The cut-off ditch aims to intercept the flood wave and connect to the backwater system to recycle. The water inflow is calculated according to local hydro-geological information and dam backwater area.

2.3. The monitoring equipment installation

In this research, the saturated line changes regulation was observed by the water level monitor buried in the physical model dam, the tailings dam displacement variation was monitored by radar interferometry, the evolution of dam breach was traced by the high-speed camera, and the breach flow changes and the flood peak process was detected by the LGY-III type multi-functional intelligent flow meter. Experiment monitoring spots and equipment layout is shown in Figure 1.

The dam failure displacements regulation was detected by the IBIS-S radar interferometry amounted at the bottom of the cutoff-ditch. Because the IBIS-S radar interferometry is only available in the distance resolution (resolution 0.5m) without the angle resolution, the dam cannot be defined. In this condition, several key spots were selected for real-time monitoring as long as the distance interferometry permits. Tailings dam physical model was divided into several blocks (pixel unit), the pixel unit size depended on the distance to the equipment location. According to the purpose of dam failure experiment, the key spots were at the bottom of the dam, in the middle of the dam, and on the top of the dam separately.

To monitor the water level flow, breach flow and the dam failure flood flow, LGY-III type eight-channel multi-functional intelligent flow meter was adapted, which was equipped with multi-function smart new spin slurry flow sensor, rotary pulp helix angle, pitch, and rotating plasma with 15mm diameters. The rotating plasma reflective surface uses advanced plating technology, wear-resistant, strong signal. The starting velocity, speed range, linearity, concentricity, rate of coefficient and standard deviation sensors and other indicators have greatly improved and enhanced. The initial velocity is less than 1cm/s. There were eight monitoring spots, two of which were in the dam impoundment, one was set on the beach, one was settled on the inner slope, and three were on the top of the dam, one was on the outer slope, one was set at the bottom of the dam, and the last one was set at downstream in 1m.

The saturated lines monitoring holes were set at outer slope, dam crest and the inner slope, which were made by PVC pipes in 100 mm diameter and 96cm height. After the seepage treatment, each of the saturation lines monitoring holes were at about 50cm intervals. In this experiment, a self-designed handheld DC inductance indicator was invested to measure the saturated lines water level continuously. The accuracy and high sensitivity indicator was suitable for this experiment. Tailings dam failure experiment results and analyzes
According to the similarity theory, the tailings dam failure flood physical model should be built first and all the sensors should be installed completely. Through the water system to pump water into the flood control area until the beach length reached 1.2m. After the water has saturated the beach and the dam, water level was raised to the highest designed evolution and the current saturation line height was measured when the beach length was 20cm. Finally, water was pumped again until the tailings dam model flood overtopping failure happened. The dam displacements, saturated lines water level and evolution of the breach were monitored by a variety of monitoring equipment and sensors.

2.4. The deformation results of tailings dam failure

Water was pumped into the physical model area at 2 m3/min speed by the water injection system to simulate the flood. As the water level increased and the dam stability changed, the overtopping failure happened at 0.2m from spot WY-A when the highest water level was 45cm. Dam displacement results of each monitored spot was shown in figure 6. The dam displacement of WY-A spot was shown in figure 6a. As the water level increased, WY-A displacement increased gradually until it collapsed when the maximum of displacement was 10.03mm after water was pumped 4356s. The dam displacement of WY-B spot was shown in figure 6b. As the water level increased, WY-B displacement increased gradually until it collapsed when the maximum of displacement was 9mm after water was pumped 4360s. The dam displacement of WY-C spot was shown in figure 6c. As the water level increased, WY-C displacement increased gradually until it collapsed when the maximum of displacement was 4.52mm after water was pumped 4362s. The dam displacement of WY-D spot was shown in figure 6d. As the water level increased, WY-D displacement increased gradually until it collapsed when the maximum of displacement was 4.9mm after water was pumped 4362s.

From the experiment results, the tailings dam physical model dam produced stable settlement and
expansion until a steady state after full infiltration because of water infiltration and penetration during the flood simulation. In flood conditions, the tailings dam physical model showed slope displacement and peak displacement when water level exceeded the highest designed elevation. All the monitored spots took place significant displacement trends. In the mines, Trimble S8 total station series automatic displacement monitoring system has been installed in the tailings dam to monitor the dam displacement continuously. All the displacement data should be analyzed monthly. If there is a large displacement peak value or a movement trend means there are safety risks in the tailings dam. Some safety measures such as reduce the water level or reinforcement the bank should be done.

2.5. The saturation line results of tailings dam failure

In the tailings dam failure experiment, first water was pumped to 15cm to fully infiltrate the dam until the saturated lines were wetting balance. Then water was pumped again to the highest water level 32cm to record the saturated lines water level. At last, water was pumped continuously until the overtopping failure happened. The saturated lines water level was recorded at 5min interval. The saturated lines water level versus time curve was shown in figure 3.

Fig.3. Saturated lines water level monitoring

JRX01 was at the bottom of the inner slope, JRX02 was on the crest of the dam, JRX03 located at the outer slope. Each of the saturated lines was 50cm interval in distance. From the experiment results, the infiltration rate in the basic rate synchronization after full infiltration when the water level was raised. JRX01 reached a wetting balance at 145min while the water level was 31cm. At this time, JRX02, JRX03 were zero and JRX 01 was 3.7cm in height. This means the water has not penetrated throughout the dam foundation. The dam body is still stable condition. To simulate flood conditions, JRX01, JRX02, JRX03 was 42.7 cm, 31.8 cm and 20.8 cm respectively in 270 min when water level was 43cm. Tailings dam overtopping occurred at 290min, all the saturation lines water levels decline to zero in the following 10 min until the water flowed out completely.

2.6. The evolution of tailings dam failure

To analyze the tailings dam flood overtopping failure development and evolution, 10 cm × 10 cm finite element mesh was used on the outer slope. With the overtopping over flow, the flow saturated sand gradually at the breach. For the tailings gravity, the dam slips occurred and the overtopping evolution was shown in figure 4. After 2min of the flood failure, the breach was 4cm and water head was within 20cm under the crest with 4mm dam fracture in “Y” shape expansion. The fracture length was 35cm, and the flow was 9.68cm/s as shown in figure 4a. In the next 15s, the sustained head discharged 20cm crack at making erosion dam collapses which led to the dam unstable fracture and subsequently collapsed with the
flow at 11.28 cm/s as shown in figure 4b. As the erosion rose to 35cm, there were vertical fracture at 50cm on the crest and the flow was 13.42cm/s as shown in figure 4d.

![Figure 4b](image1.png) ![Figure 4c](image2.png)  
(a) T=292min  (b) T=292min15s

![Figure 4d](image3.png)  
(c) T=292min30s  (d) T=292min35s

From the results, the mainly damage of the tailings dam flood overtopping is the erosion of the discharged water head which carry away the dam tailings resulted in the upper dam instability. Then the breach grows big and longitudinal cracks appeared at the dam. As the breach increased, the whole tailings dam failed eventually. In this process, the breach flow keeps increased, the ability of carrying sand enhances and the erosion increased that result in the tailings failure. In the daily tailings dam management, especially the flood period, water level should be monitored closely and the flood drainage facilities should double check to make sure the flood drainage ability. If the tailings dam flood overtopping failure has happened, some measure such as the using of sandbags clogging breach, increase the discharge capacity. In the meanwhile, pave the cut-off ditch or drainage pipe to reduce the erosion of the dam slope could be preventing the dam failure rapidly.

3. Conclusion

The tailings dam flood overtopping failure evolution pattern experiment results show that:

(1) The tailings dam flood overtopping failure belongs to the erosion collapse type. The saturation line water level increases slow that the water level. The overflow results in the erosion and leads to the dam destroyed gradually.

(2) The final breach of the tailings dam flood overtopping failure depends on the overflow erosion of the outer dam slope. The overflow of the tailings dam saturates the dam sand and forms the semi-saturated debris flows to discharge downstream to the dam foundation. The bottom of the dam appears saturation effect during the collapse.
(3) The dam displacements are related to the saturation degree. The sliding displacements are big as the saturation lines are high. In the evolution of the dam collapse, the damage begins from the dam slope foot, and then develops upward and the whole dam failure happens finally.

(4) The experiment of the tailings dam model is made of the coarse tailings. The whole tailings dam is regarded as the same material. In the future experiment, a variety of tailings are adapted will help in-depth study the tailings dam collapse mechanism and break mode.

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