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# Study on the Process and Mechanism of Indoor Overtopping Dam-Failure of Tailings Dam Model Experiment under the Rainfall

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## Abstract

Rainfall is an important reason for the break of the tailings dam, the most common mode for the failure of tailings dam is overtopping. In this paper, using the self-designed test device of tailings dam-failure and upstream tailings dam as the research object, experimental study of indoor dam break mode carried out and the analysis of overtopping dam-failure mechanism under the rainfall conditions. The results shows that: the height of saturation line affected by the water level in the process of rainfall is obvious, in the early rainfall, the reservoir water level exceeds the saturation line height. When tailings saturated, the rate of saturation line is consistent with the rate of reservoir water level, infiltration surface is an irregular surface decreasing along the direction of primary dam. There is a significant size grading phenomenon during tailings drawing due to the flow separation effect, the content of fine particles tailings with deposition distance increase showed an increasing

trend, while the content of coarse particles tailings with deposition distance increase showed an decreasing trend. The mechanism and process of overtopping dam-failure are analyzed during the rainfall. The process of overtopping dam-failure contains: fine gullies formed by erosion, flow overtopping, small "Scarp" formed, large "Scarp" formed, breach expansion rapidly and dam berak completely. Research results have a certain theoretical guidance and engineering application value for improving the theory of dam-failure.

## Key words

Model test, Mechanism of dam break, Dam failure caused by overtopping, Scarp erosion

## 1. Introduction

Tailings dam is a great dangerous source which possesses high potential, and once the tailings has been broken, not only make the country suffered huge economic losses, but also endanger the life and property safety of the downstream residents, at the same time caused serious environmental and ecological damage. Based on the statistic data from 2007 to 2015 in State Administration of Work Safety, there were 11,359 tailings in 2005, including 1,102 tailings had on-line monitoring technique, 31 dangerous tailings, 1,451 mountain dam and 466 riverside dam. These tailings were in high safety risk, and most of them located in upstream of the area with dense population, it making a Threat to the town and village residents' lives and property safety in the downstream of the reservoir area. At present, more than 90% tailings in our country used upstream dam construction method, upstream tailings dam have the feature of complicated dam structures, high water table level, complicated dam-break mechanism. In recent years, upstream tailings accidents occur frequently[1,2], Rico, Azam[3,4] have counted 218 tailings dam accidents all over the world from 1910 to 2009, the analysis shows that the first cause of tailings accident is unusual rainfall, almost 76% tailings are upstream tailings. Aiming at the problem of dam-break under the condition of unusual rainfall. Maria[5,9] has developed the study on precipitation infiltration mechanism, established the corresponding calculation model under the action of rainfall, and analyzed the change law of saturation line and its effect on dam stability. The whole process of instability and failure of tailings dam can be present clearly to researcher by indoor model experiment. Rico[3] established the relationship between tailings dam geometric parameters (dam height, storage capacity, etc.) and the characteristics of fluid tailings, put forward the correlation between the erosion, scarp and soil

parameter. Hanson and Mainali[10,11] have analyzed development process of breach through the simulation of field and indoor experiments. Yin Guang-zhi and Chen Shui-sheng[12,13] have developed model test for the mechanism of dam-break. Zhang Xing-kai and Zhang Hong-wu[14,15 ]have explored the evolution law of overtopping dam-failure under flood by indoor tailings dam model experiment.

In terms of stability and dam-failure prediction model of tailings dam, Gens and Maria[16,17] have studied the law of slope stability changes along with rainfall, and put forward the gradual destruction mode of tailings. Salgueiro[18] has evaluated the risk of dam-failure through the data before the disasters and accident consequence. Zhao Tian-long[19] has analyzed the mechanisms of dam-failure and the process of breach extend, and pointed out the primary cause for the failure of tailings dam at home and abroad. Currently, although there have been used 1,102 on-line monitoring system of tailings dam in China and its technology is relatively mature. The interaction of various factors makes the prediction of unstable failure of tailings dam have strong uncertainties because of the complex and changeable factors that affect the unstable failure of tailings dam.

So in terms of tailings dam safety diagnosis system, there is still lack of some relevant theoretical bases, especially in the mechanisms of dam-failure under the condition of unusual rainfall, more experimental data of dam-break are required to supplement and perfect early warning model. In this paper, the upstream tailings dam is studied as the research object. Using the self-designed test device of tailings dam-failure, indoor heap (break through) dam mode experimental study was conducted under the condition of unusual rainfall, the overtopping dam-failure and the whole process of breach extend were analyzed under the overall rainfall conditions, put forward the mechanism of upstream tailings dam overtopping dam-failure on strong rainfall condition. Research results have a certain theoretical guidance and engineering application value for improving and establishing early warning model of upstream tailings dam.

## 2. Tailings dam heap(collapse) dam model test

### 2. 1 Similarity conditions

The process of dam-failure is very complex, involves hydraulics, soil mechanics, and mechanics of soil transport. The similar conditions usually incompatible, and the test model cannot meet all similar conditions. As a result, this indoor model test abandons the similar generality,

broadening the similar rules, selecting the main acting force to make analysis. The similarity conditions as follows. Water flow perturbation led to deformation of tailings, which is mainly related to gravity and inertia of tailings. As a result, the gravity and the inertia of water flow and tailings should meet gravity similarity condition. The water flow in the process of dam-break is hyper-concentrated flow, which should meet the movement similarity of water flow and tailings. According to the general ore drawing flow and combined with the proportion 1: $\lambda$, solving the dam construction speed and flow in the process of dam construction. In this indoor model test, we mainly consider accumulation effect of particles during the movement of tailings. Explaining the phenomenon of dam-failure by using macroscopic physical quantity, but the condition of geometric similarity of single particles are neglected.

## 2. 2 Indoor dam construction model

In this paper, the upstream tailings dam of valley type studied as the research object, which reduce scale is 1:50. Earth-rock dam is used as primary dam, using coarse tailings to accumulate fourth sub-dam of indoor model, the accumulate dam and primary dam are trapezoid.

## 2. 3 Experiment device

The indoor model test device of tailings dam primarily includes:

**Rainfall-reservoir water level fluctuation system**: it is consists of rainfall simulator and external water source. The rainfall simulator could simulate artificial rainfall, different type rainfall, different duration of rainfall and rainfall intensity, it could record the law of rainfall changes along with time. The external water source could simulate the change of reservoir water level.

**Monitoring system**: it is made up of saturation line monitoring, reservoir water level monitoring and auto photographing system. Monitoring devices could record the dam development process along with time, and the high-speed camera could log the whole process of dam-break.

**Drawing device**: the device for preparation and agitation of tailing.

### 2. 3. 1 Rainfall device

At present, since the spray pattern of rainfall has characteristics, that it easy to control rainfall, enhance rainfall uniformity and became the most widely used types of domestic and foreign. Therefore, the test device use a jet rainfall pattern, then to drill small holes in some parallel thin tube and water spouted from the hole to form raindrops falling to the ground. As it is shown in the figure

1.

## 2. 3. 2 The saturation line measuring device

The level of saturation line will impact the stability of tailings dam. So we use 25mm diameter PVC pipe to monitor the library saturation line changes in the process of model experiment under the condition of rainfall. We arranged three rows of vertical drainage pipe along with ditch. The bottom of the drainage tube is connect with PVC pipe and the PVC pipe is connect with the outside glass pipe with graduation. We can get the saturation water level according to the transparent pipe level scale. In order to distinguish easily, each section measure four point of saturation line numbers. The three rows of four riser tubes are numbered1-1, 1-2, 1-3, 1-4; 2-1, 2-2, 2-3, 2-4; 3-1, 3-2, 3-3, 3-4 and marked X, Y, Z coordinate system, as it is shown in the figure 2.


Fig. 1. Rain pipe arrange schematic diagram


Fig .2. The saturation line piping

## 3. The particle size deposits of dispersed ore drawing in the front of the dam

In order to prevent the water-sand separator phenomenon during indoor dam construction model, the tailings concentration configured in the process of ore drawing cannot be too low. At the same time, also to prevent the tailings appears blocking pipe phenomenon due to high concentration, and make sure that tailings slurry can flow into the dam rely on gravity. Therefore, tailings preparation concentration of 60-75%, this concentration allows tailings rely on gravity flow into the dam during dam construction experiment. Dispersed ore drawing in the front of the dam during dam construction by using 50mm diameter PVC pipe. The pipe connection tailings hopper, four ore drawing tube placed in front of the dam. In the ore drawing test, tailings and water are mixed by using hand-held blender and poured into the hopper through the discharge pipe from the mine flow into the library, appropriately adjusted ore drawing position of the tube, so that the tailings deposited

along the valley. The coarse tailings made trapezoid accumulate dam waiting for the tailings of reservoir is flat with the primary dam, pile up level by level, until the fourth sub-dam is flat. In the experiment of ore drawing, despite the concentration of tailings is higher, but it still has a certain flow erosion ability, when the tailings slurry through the discharge pipe into the library, in front of the library will form small gully, the tailings form "channeling or overflow" slurry along a small gully. The lower pulp density and the gully more obvious. The tailings slurry in the library middle and library end places show "thin stream," "laminar" flow state. There is a significant size grading phenomenon due to the flow separation effect, the content of fine particles tailings with deposition distance increase showed an increasing trend, while the content of coarse particles tailings with deposition distance increase showed a decreasing trend throughout the process of tailings slurry flow.

## 4. Test of overtopping dam-failure under overall rainfall conditions

### 4.1 The varying law of dam saturation line

To study the dam-failure process of upstream-type tailings dam under rainfall conditions, a indoor dam-failure model of tailings dam under rainfall conditions was set up, the constant rain intensity was 105mm/h. In the rainfall experiment, different period rainfall saturation value measured by saturation line measuring device as figure. 2 have shown, the height of water level and saturation section changes with time before dam break is shown in table 1, the different saturation surface value was tested in different rainfall periods is shown in the figure. 3, where X, Y and Z correspond to the coordinate points in figure. 2 respectively. The in-tank water level and infiltration line were respectively recorded every 30 minutes. The whole rainfall process lasted for 4 hours and 21 minutes.

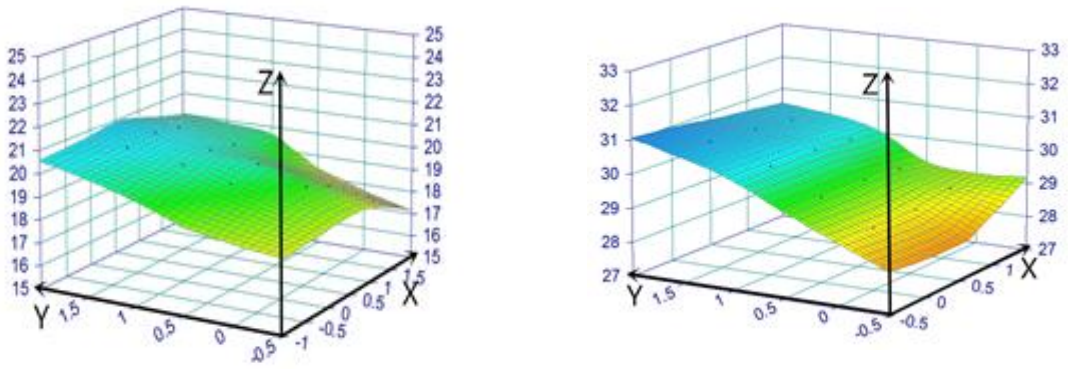
The table 1 shows the library water level variation and saturation section changes with time, it can be seen from the table, the water level height and saturation section height rises with rainfall time. In the early rainfall, the increased rate of saturation line rate is high, as the rain continued, the increased rate of saturation line gradually smaller until a stable value before dam-failure. Due to the tailings pore pressure, saturation line lags behind the initial water level height in the early rainfall, rate of saturation line rise keep pace with the rate of water level rise after tailings saturated until the water level rises surpass the saturation line test pipe, saturation line height consistent with the water level in the late rains. So, the in-tank water level variation needs to be tested in time and flood

prevention need to be well prepared in strong rainfall.

Table.1. The height of water level and saturation section changes with time before dam break

| Rainfall time | Water level height | Saturation section1-4 | Saturation section2-4 | Saturation section3-4 |
|---|---|---|---|---|
| 0 min | 9.5 cm | 4.1 cm | 4.0 cm | 4.3 cm |
| 30 min | 16.7 cm | 14.7 cm | 14.2 cm | 15.6 cm |
| 60 min | 20.5 cm | 19.6 cm | 18.9 cm | 19.2 cm |
| 90 min | 24.0 cm | 23.2 cm | 23.1 cm | 23.0 cm |
| 120 min | 26.7 cm | 25.8 cm | 25.3 cm | 25.2 cm |
| 150 min | 28.8 cm | 27.6 cm | 27.4 cm | 27.3 cm |
| 180 min | 30.6 cm | 29.8 cm | 29.5 cm | 29.2 cm |
| 210 min | 32.0 cm | 31.2 cm | 31.5 cm | 31.4 cm |
| 240 min | 35.0 cm | 34.6 cm | 34.8 cm | 34.7 cm |

The figure. 3 shows that the height of saturation line increases over time under rainfall and finally reach saturation balance. Since the primary dam is permeable dam and laying drain pipes, library water continues to flow to the dam outside. Due to the hydraulic gradient, it can be seen from the figure 4, the saturation surface is not a plane, but a surface continue to lower along the direction of the primary dam, it is mainly due to the tailings permeability coefficient, water content and the loose-degree difference. From the height of water level and saturation line changes, the library water level rises have a significant impact on the height of saturation line. It can also explain strengthen tailings drainage measures can reduce the saturation line height effectively .




(a) 60min saturation surface height (b) 180min saturation surface height

Fig.3. Different periods of rainfall saturation surface three-dimensional view

## 4. 2 Overtopping dam-failure and the development of breach

As the rainfall continues, the in-tank water level grows faster than outward infiltration speed, thus the height of water level is higher than accumulate dam. When in-tank water level is higher than the lowest point of the dam body, overtopping dam-failure appears. The dam-failure model test is as shown in the figure 4.

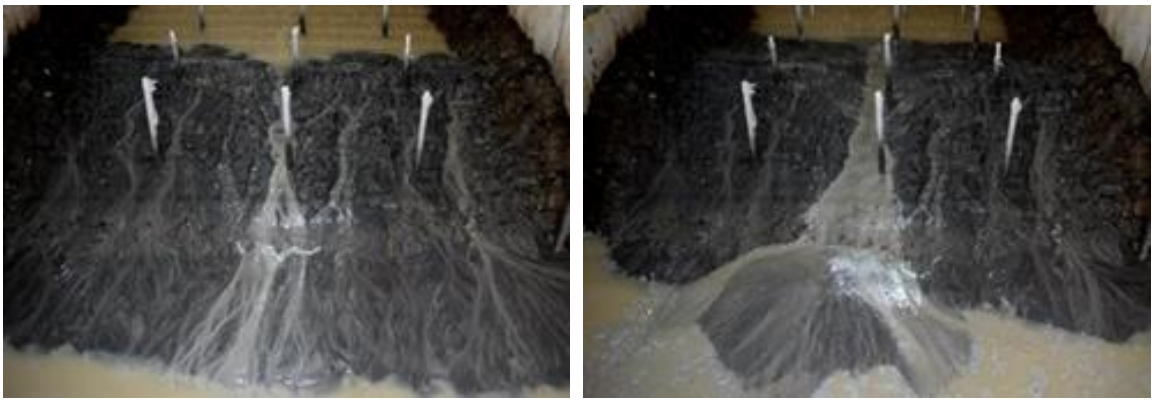


Fig .4. Tailing dam break breach evolution

The dam-failure mechanism of tailings dam is very complex which involves multiple physical processes including mechanics features of tailings material, flood overtopping and brushing dam, tailings stability analysis, which is the issue that rock mechanics, hydraulics and silt movement mechanics infiltrate and others coupled. In this in-door dam-failure model test, in consideration of the accumulating effect of particle movement in the process of tailing deformation, the macroscopic physical quantity is used for the demonstration of the development process of the breach erosion during dam-failure.

Regarding the shape of breach, the field indoor dam-failure test indicates that, when tailings dam overtopping, the overflow firstly gathers on the downstream surface and form a gully which gradually expands along upstream and then forms an initial breach on the body and top of the dam. With the overtopping water speed increase, the erosion of the dam body gets more aggravated and the breach gets deeper and wider, meanwhile intermittent unstable collapse occurs in the soil mass beside the breach. In consequence it can be considered that the overtopping dam-failure and the development process of breach includes “continuous longitudinal cut and transverse erosion caused by water erosion" and “intermittent lateral extension caused by breach slope instability and collapse”, the process of indoor dam-failure and breach development under the conditions of rainfall as follows:

**Small gully caused by rainfall erosion:** in the process of rainfall, the tailings dam surface is

affected by splash erosion and sheet erosion of raindrop, and some scaly grooves and ripples are formed on the slope. As rainfall continued, the rainwater on the slope continuously gathers to form rills and gully net on the slope with the development of brush.

**Formation of gully erosion and dam overtopping:** in the preliminary phase of overflow, the tailings sand is of very low density, approximate that of clean water flow. As time goes by, there appears brush like small gullies on the downstream slope of the dam, the gullies merge and divide with gully bottom erosion, on the upper slope abundant water flow with strong erosion ability, which strongly undercuts the slope body and saps the bottom soil to form a connecting gully, gully stream was formed attributing to the gully and water interaction. When the in-tank water level is higher than the minimum elevation of the dam top, the water begins to overflow and produces breach in the middle of dam.

**Gully formation mechanism of multi-step "scarp":** erosion mechanism varies with places, overflow is water erosion near the crest, erosion from the downstream to center dam body produced by bed load assembles, in the bottom of the slope is tailings flow erosion. Due to the lower part of slope surface erosion rate is greater than the upper slope surface, tiny scarps formed are most likely to start where the fractures exist in the dam and finally forms a bigger gully which contains multiple small scarp in the step shape.

**Big "scarp" formation and breach broadening:** multiple small "scarps" retreat along upstream and broaden continuously over time, finally forms a big "scarp". With the affect of water flow, the"scarp"up gradually, until the upstream crest edge. Thereafter once the "scarp" develops along upstream, the crest of breach will be reduced, the water and tailings flow will be maximum, "scarp" brushing like "waterfall" will appear. Multiple step-like "scarps" retreat along upstream continuously with time, and with constantly brushing of water, the later erosion causes the broadening of breach width and finally the gully becomes a big "scarp". The development duration of the breach depends on the brushing of water and tailings flow to the dam, also related with the water flow, dam height, material and material density of dam construction.

**Rapid expansion of breach:** with the height of the dam top reduce, the water flow in breach will increase rapidly, and then the breach expands to the depth and both sides.

**Complete dam-failure:** the depth of breach remained unchanged, the breach develops mainly in the transverse direction until the dam-failure completely, breach appears like debris flow after dam-failure.

## 5. Conclusion

In-door model test is one of the important scientific methods of researching some complex engineering problems. It reproduces the phenomenons and problems so that people can control the conditions and parameters of the test, which simplifies the test, reduces research period and make it possible for researchers to understand, solve and describe the problems from the angle of physics, so it is very popular among various scientific researchers. In this paper, indoor heap (break through) dam mode experimental study was conducted under the condition of rainfall, the mechanism of overtopping dam-failure and the whole process of breach extend were analyzed under the overall rainfall conditions, and the result shows: In the indoor ore-drawing experiment, there is a significant size grading phenomenon due to the flow separation effect, the tailings slurry formed “channeling or cross flow”. When the tailings slurry flow into the tank through the ore drawing tube, it flow in “film flow” and “laminar flow” in the dam end. The in-tank water level variance has an obvious impact on the height variance of saturation line. In the preliminary stage of rainfall, the saturation line lags behind the height of in-tank water level, after tailings saturated, the rate of saturation line rise keep pace with the rate of water level rise until the late rains as the water level rises surpass the saturation line test pipe, saturation line height consistent with the water level. The saturation line is not a plane, but a surface continue to lower along the direction of the primary dam, this is mainly due to the tailings permeability coefficient, water content and the loose-degree difference.

The experimental result of in-door dam-failure indicates that, with the continuous brushing of overtopping flow, the breach gets wider and deeper, and intermittent collapse of the soil mass appears beside the breach, thus it can be considered that the overtopping dam-failure and development process of breach includes " continuous longitudinal cut and transverse erosion caused by water erosion" and “intermittent lateral extension caused by breach slope instability and collapse”, the process of indoor dam-failure and breach development under the conditions of rainfall include : fine gullies formed by erosion, dam overtopping, form a multi-stepped small "scarp", formation of large "scarp", breach rapid expansion, dam burst completely.

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