Similarity Test of Rainfall Infiltration Model for Tailings Dam Slope

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Abstract. In order to explore the rainfall infiltration mechanism of tailings dam and its influence on dam properties, experiments were carried out by self-made tailings dam sand trough model and rainfall simulation system. The dynamic characteristics of infiltration rate with different rainfall intensity were obtained. The results show that in the process of rainfall infiltration, saturation is the first place under the dam. But the final water content remained stable and the difference was small. For the same rainfall intensity, the rainfall infiltration process of tailings dam can be divided into three stages. The water accumulation point is 0.59 mm/min and the saturation point is 0.23 mm/min. Different rainfall intensities have the same trend in the infiltration process. Finally, it tends to saturate permeability coefficient Ks. The infiltration rates of the three rainfall intensities decreased by 81%, 60% and 21% respectively at the two boundary points.

1. Introduction
There are many factors affecting the stability of tailings dam. Among them, rainfall is one of the most common factors inducing tailings dam failure[1]. Especially, the influence of rainfall infiltration on dam stability is the most lasting and obvious [2-3]. Rainfall infiltration process of tailings dam slope is similar to that of general unsaturated soil slope. Based on the rainfall model test, the suction response speed and the influence depth of tailings dam shallow layer in the process of rainfall are analyzed. In view of the change of seepage field in the process of rainfall infiltration of tailings dam, Sun Enji et al. [4] analyzed and calculated the transient stability of tailings dam under rainfall conditions using the theory of rainfall infiltration. With the change of rainfall conditions, the seepage field in tailings reservoir will change accordingly. According to the strength theory of unsaturated soil, the influence of rainfall infiltration and pore water pressure should be considered in slope stability analysis[5-7].

In order to study the mechanism of rainfall infiltration and its influence on dam stability, a reasonable and effective method is needed. The influence mechanism of rainfall infiltration on dam slope stability and its manifestation are analyzed. In the sand-trough model device of tailings dam, tailings dam is built according to the actual slope ratio of tailings dam slope. At the same time, "pipe
network rainfall device was made to simulate rainfall. Under the condition that the initial water content, infiltration and water content (saturation) have been determined, the distribution and dynamic evolution of infiltration water have been measured in real time by Luge L99-TS-2 soil moisture tester.

2.  Theory and Methods

2.1.  Model similarity theory of rainfall infiltration
According to the Third Similarity Theorem, for phenomena with the same characteristics, when the single-valued conditions (geometric properties of the system, physical properties of the medium, boundary conditions and initial conditions) are similar, and the similarity criteria composed of physical quantities of the single-valued conditions are equal in value, the similarity criterion can be satisfied [8].

Geometric similarity. Let's set the length similarity constant \( \lambda_L = L_p / L_m \). According to the actual parameters of a tailings reservoir project in Sichuan Province, the length scale \( \lambda_L \) is determined to be 1:200. The prototype and model have the same downstream slope ratio. The total slope ratio downstream of prototype and model is the same.

Motion similarity. Assuming that prototypes and models have velocities of \( v_p \) and \( v_m \) respectively. Permeability coefficients are \( k_p \) and \( k_m \), respectively. Then the velocity similarity coefficient \( \lambda_v = v_p / v_m = k_p / k_m \). Natural raw tailings are selected in the test, so the ratio of permeability coefficient \( k \) is 1, that is, the velocity similarity coefficient is 1.

Dynamic similarity. Newton's second law is applied to the fluid micro-clusters in the flow field, and the dynamic similarity coefficient \( \lambda_d = \rho L_2 v^2 \). Among them, \( \rho \) is a density similarity constant. \( N_e = F / \rho L^2 v^2 \) is called Newton number. If the prototype is similar to the two fluids of the model, its Newton number is equal, that is \( (N_e)_p = (N_e)_m \). Because the original tailings are used in the model test, it can be considered that the density \( \rho \) is equal. Therefore, the model test satisfies the dynamic similarity [9].

Similarity of initial and boundary conditions. Initial conditions: suitable for unsteady flow, the initial profile water content of tailings dam prototype and model is equal to 5%.

Boundary conditions: there are three factors: geometry, motion and dynamics. The pressure on the free surface of the upper boundary is atmospheric pressure. The normal velocity on the solid boundary is 0. According to the "flood control standard of tailings reservoir", the average rainfall for many years and the recurrence period of flood are 100 years, 200 years, 500 years and the possible maximum flood (PMF), respectively.

2.2.  Testing device and methods

2.2.1.  Basic design of test model. The initial water content in the dam body is about 12% (the actual water content in the prototype). The downstream slope ratio of the initial dam is 1:2.5. The downstream slope ratio of the accumulating dam is 1:4.5. Coarse-grained tailings are deposited in front of the dam. The tailings are evenly dispersed and compacted during dam construction to maintain a certain strength of the dam body. In order to further improve the similarity ratio between the prototype and the model of tailings dam, the model of tailings dam was built according to the scheme, and then the model of tailings dam was stationary for 24 hours to enhance its consolidation degree.

2.2.2.  Fabrication of rainfall simulation system. Indoor artificial rainfall simulation system has three main types: pipe network, jet and rotary. According to the characteristics of different types of rainfall simulation system and the actual conditions of this experiment, the pipe network rainfall simulation system was used to carry out the experiment. Considering the sand trough model of tailings dam used in previous tests, the network rainfall simulation system designed in this paper is a rectangular iron container with a bottom area slightly smaller than the bottom area of the sand trough model. A circle
of iron rings with a cross-sectional area larger than the surface area is arranged around the middle and lower parts of the container to fix the container. At the same time, drill uniform fine holes in the bottom of the container, as shown in Figure 1.

![Figure 1](image1.png)

**Figure 1** Design sketch of pipe network rainfall simulation device.

2.2.3. Rainfall intensity calibration. Rainfall intensity is calibrated by the method of total rainfall field connection. Then, the average rainfall intensity of the whole test site was calculated. This method avoids the errors caused by the heterogeneity of rainfall (in general, 80% uniformity can be considered to meet the needs of the test). It has high observation accuracy. The relationship between the cumulative rainfall volume \( V_B \) and the corresponding time \( T \) under the rainfall intensity is plotted, as shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** Test cumulative rainfall and time rate curve.

As can be seen from Figure 2, the rainfall intensity remained stable during the experiment. \( V_B \) and \( T \) have good linear correlation. The slope is the simulated rainfall \( Q \) per unit time, which is \( 4.64 \times 10^{-5} \text{m}^3/\text{s} \). Since the horizontal projection area, \( A \) of the sand channel model of tailings dam is known, the rainfall intensity \( I \) can be calculated according to the following formula:

\[
I = 6 \times 10^4 \frac{Q}{A} \tag{1}
\]

In the formula \( Q \) is the unit time rainfall, \( 4.64 \times 10^{-5} \text{m}^3/\text{s} \). \( A \) is the horizontal projection area of the sand trough model, \( 0.464 \text{ m}^2 \). Rainfall intensity \( I \) was 0.6 mm/min. Because the method is used to obtain the observation results of continuous multiple rainfall intensities over a short duration of the whole rainfall field. Therefore, this method can not only accurately measure the rainfall intensity of the rainfall test, but also test the stability of the rainfall process.
2.2.4. Determination of rainfall infiltration and water content. Maintain the above-mentioned equivalent rainfall intensity and quickly remove the plastic sheet for the simulation of the tailings dam rainfall. At the same time, start timing and switch to a 50ml measuring cylinder to fill the running water. The difference between the total rainfall and the runoff can be considered as the infiltration amount q. The ratio of the infiltration amount to the time t is the infiltration rate I.

In order to analyze the dynamic change of water content in the dam slope during rainfall, the soil moisture meter was used to observe and record the water content of the upper, middle and lower parts of the dam slope soil every 5 minutes. In addition, by observing and recording the change of the height of the piezometer, the steady state of seepage in the soil of the tailings dam slope is judged, and the change of pore water pressure in the soil can also be characterized [10].

After the first set of tests, adjust the amount of water in the rainer according to the same method and procedure as above. The experiments were carried out again under the rainfall intensity less than and greater than 0.6mm/min, and the infiltration laws of the tailings dam slope under different rainfall intensities were studied.

3. Results

3.1. Analysis of the law of water content and pressure change in dam body

The actual initial water content of the upper, middle and lower parts of the tailings dam is 9.6%, 10.7% and 13.5%, respectively. The saturated permeability coefficient is 3.54E-4cm/s, i.e. 0.21 mm/min. The three different rainfall intensities R(t) were 0.7 mm/min, 0.35 mm/min and 1.4 mm/min, respectively. The experimental results are as follows.

Change of water content in dam body. In the process of rainfall, the water content in different positions of dam body is different. Under the condition of rainfall intensity of 0.7 mm/min, the variation of water content with time is shown in Figure 3.

![Figure 3 Variation of water content with time in different positions of dam.](image)

From Figure 3, it can be seen that the water content increases fastest within 15 minutes of rainfall onset, and the change of water content decreases significantly after 55 minutes. The lower part of the dam body reaches saturation first, followed by the middle and upper part. In addition, the higher the dam position, the lower the initial water content. But ultimately, the water content remains stable, and there is little difference in size.

Variation of pore water pressure in dam body. The variation of pore water pressure can be characterized by the rising height of water level in the piezometric tube, as shown in Figure 4.
Analysis of the test results shows that there are significant differences in pore water pressure at different locations within the dam. The pore water pressure in the upper position is minimal during the rainfall process. The pore water pressure changes most at the lower position. Under the same rainfall intensity, the pore water pressure gradually increases with the duration of rainfall. When the water content in the soil is close to the saturated water content, the rainwater is no longer infiltrated. Then the water pressure tends to be stable and there is no significant change.

3.2. Analysis of the results and laws of rainfall infiltration test of the dam

3.2.1. Change law of infiltration rate under constant rainfall conditions. The representative position of the tailings dam is selected to study the variation of rainfall infiltration when the rainfall intensity is 0.6 mm/min. The result is shown in Figure 5.

For the same rainfall intensity. In the early stage of rainfall infiltration, due to the relatively dry surface layer of soil, the infiltration capacity of soil is greater than the rainfall intensity. The actual infiltration rate at this stage is still equal to the rainfall intensity. Under the condition that the rainfall intensity is stable, the infiltration rate of the soil within 50 min of infiltration remains basically unchanged. This phase is the rainfall intensity control phase (or water supply control phase).
With the continuous infiltration of rainwater, the water content of surface soil increases rapidly. However, the infiltration capacity of dam slope soil decreases gradually. When the infiltration time is 50 minutes, the infiltration rate is about 0.59 mm/min, reaching the volume water point of soil. The infiltration capacity of dam slope soil will be less than rainfall intensity. Infiltration rate decreases rapidly, and some rainwater forms surface runoff. This stage is the infiltration capacity control stage (or unsaturated soil control stage).

After 80 minutes of infiltration, the infiltration rate decreased to 0.23 mm/min. The slope of I ~ t curve is close to 0. The water content of the whole tailings dam model reaches the saturation point. At this time, the infiltration rate is close to the saturated permeability coefficient \( K_s \) of the soil. Then it is the saturated soil control stage.

Among the three rainfall stages mentioned above, the water accumulation point of 0.59 mm/min and the saturation point of 0.23 mm/min are the dividing points of the three stages. The seepage in soil belongs to saturated-unsaturated seepage.

3.2.2. change law of infiltration rate under different rainfall intensities. Similarly, the middle part of a typical tailings dam is selected to study the variation of infiltration rate with time under different rainfall intensities, as shown in Figure 6.

![Figure 6](image_url)

According to the test results, the three rainfall intensities are greater than the saturated permeability coefficient of the dam slope soil. For different rainfall intensities, the tailings dam rainfall infiltration process has the following characteristics:

Different rainfall intensities show the same trend of rain infiltration. That is, the three curves all show from basically constant to gradually decrease, and finally tend to the same limit infiltration rate (saturated permeability coefficient \( K_s \)), about 0.23 mm/min. However, the three curves are not the displacement segments of the same curve along the horizontal direction.

The lower the rainfall intensity, the longer the water accumulation point appears, which are 22 min, 51 min and 94 min respectively. The time at which the saturation point appeared also prolonged as the rainfall intensity decreased, at 72 min, 94 min and 144 min, respectively. Therefore, the rainfall control phase is obviously long and the infiltration capacity control phase is shortened. From the water level to the saturation point, the greater the rainfall intensity, the greater the change in infiltration rate. The infiltration rate of the three rainfall intensities decreased by 81%, 60% and 21% in the two cut-off points, respectively.
4. Conclusions

In the process of rainfall infiltration, saturation is the first place under the dam. Next is the middle and upper position. The higher the dam position, the lower the initial water content. But the final water content remained stable, and the difference was small. There are significant differences in pore water pressure at different positions in dam body. The change of pore water pressure is the smallest in the upper part and the biggest in the lower part.

For the same rainfall intensity, the rainfall infiltration process of tailings dam can be divided into three stages: rainfall control stage, infiltration capacity control stage and saturated soil control stage. Water accumulation point and saturation point are the boundary points of three stages. The seepage process belongs to saturated-unsaturated seepage. Different rainfall intensities have the same trend in the infiltration process. Finally, it tends to saturate permeability coefficient $K_s$.

Similarity theory and model test are important theories and effective methods to study rainfall infiltration process and stability of tailings dam.

Acknowledgements

This work was financially supported by Sichuan Science and Technology Innovation Seeding Project (Grant No. 2017016).

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