Saturated-unsaturated seepage characteristics and stability analysis of tailings dam under different rainfall pattern

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Abstract

Rainfall is one of the main factors affecting the stability of tailings dams and the FLAC3D software has certain limitations in the process of tailings dam seepage analysis, making it difficult to predict the stability of the tailings dam before rainfall and formulate appropriate control measures. In the study, the corresponding relationship between the pore pressure of soil elements and the permeability coefficient of unsaturated soil was derived, and the seepage characteristic and stability of the tailings dam under rainfall were successfully simulated using the FISH language embedded the FLAC3D. The research results have practical significance during the mining process.

Keywords: Tailings dam, numerical simulation, stability analysis, rainfall pattern, permeability coefficient

Introduction

Tailings dams contain a large amount of waste rock, tailings water, smelting slag, which is due to the solid waste generated during the mining process of the mine. The solid waste in the tailings dam seriously threatens the local ecological environment of the mine. Therefore, it is necessary to ensure the stability of the tailings dam during the mining process. However, rainfall is one of the main factors threatening the stability of tailings dam. Rainfall intensity and duration are the two main factors that constitute rainfall patterns. When rainfall is the same, rainfall patterns include long-term weak rainfall, short-term strong rainfall. Different rainfall patterns have varying degrees of effects on the stability of tailings dam. During the research process, some scholars believe that short-term heavy rainfall has a certain scouring effect on the surface solid waste of tailings dam, and its effect on the ecological environment of mining areas is relatively small. There are many large-scale landslides and collapses of tailings dam occur during the period of long-term weak rainfall and periodic rainfall, in fact. Therefore, it is necessary to analyze and predict the effects of different rainfall patterns on the stability of tailings dam, in order to propose corresponding support measures and implementation plans for tailings dam before rainfall, to ensure the safety and stability of tailings dam during the rainy season.

The stability analysis and prediction simulation software for tailings dams under rainfall conditions includes for example GEO-Tailings dam or FLAC3D. Among them, GEO-Tailings dam is limited to analyzing the seepage situation of two-dimensional models in simulating and analyzing the rainfall seepage process. FLAC3D cannot consider the permeability coefficient of unsaturated soil in the process of simulating seepage, which has a certain deviation to the last calculation results of seepage field. The purpose of this study is to provide an effective method for real-time updating of the unsaturated soil permeability coefficient of tailings dams during the simulation of rainfall infiltration process using FLAC3D. It aims to analyze the infiltration line of tailings dam under different rainfall modes and predict the stable characteristics of tailings dam under different rainfall modes. The research results have important practical significance in preventing landslide accidents of tailings dam from polluting the ecological environment of mining areas during the rainy season.

Simulation analysis scheme of tailings dam seepage field during rainfall

Corresponding relationship between permeability coefficient of saturated unsaturated soil

FLAC3D is difficult to simulate fluid solid coupling, especially to assign the permeability coefficient of unsaturated soil in the process of tailings dam rainfall infiltration. The main reason is that the FISH language of FLAC3D hardly picks up the saturation on the soil element, so it is difficult to determine the permeability coefficient value of unsaturated soil. However, we have successfully solved the problem of updating the permeability coefficient of unsaturated soil in real time, the core step is to use the variable 'z_pp' in the FISH language to monitor the pore pressure value of tailings dam soil in real time and update the permeability coefficient of unsaturated soil by the formula between the permeability coefficient and pore pressure of the unsaturated soil.

In the process of rainfall infiltration, the steps of assigning the permeability coefficient of tailings dam soil mass include: (1) The z_pp value in the software is used to determine whether the soil is in the saturated state or not; (2) if the soil is in the saturated state, the permeability coefficient in the saturated state can be used as the permeability coefficient in the process of soil permeability; (3) If the soil of the tailings dam is in unsaturated state, the permeability coefficient of the unsaturated soil should be updated combining the soil water characteristic curve (Eq. 1) proposed by van Genuchten with the relationship between unsaturated permeability coefficient and saturated permeability coefficient commonly used in numerical simulation (Eq. 2).

Since only the unit pore pressure of unsaturated soil can be identified in FLAC3D, it is necessary to establish the corresponding relationship (Eq. 3) between the permeability coefficient of unsaturated soil and the pore pressure of unsaturated soil. The permeability coefficient of unsaturated soil is assigned by FISH language programming. In the process of calculating and analyzing soil seepage, if it is necessary to determine the saturation of soil, the saturation of unsaturated soil can be determined in combination with the relationship (Eq. 4) between saturation and water content.

$$\theta=\theta_r+\frac{(\theta_s-\theta_r)}{\left(1+\left(a_f(u_a-u_w)\right)^{n_f}\right)^{m_f}} \quad (1)$$

where θ is the volumetric water content of soil; θ_r is the residual volumetric water content of soil; θ_s is the saturated volumetric water content of soil; a_f, n_f, m_f are the fitting parameters of soil water characteristic curve respectively; the value of 'u_a-u_w' is the pore pressure, the ua is the air pore pressure of soil, the uw is the fluid pore pressure of soil.

$$k_s^{'}=\frac{\theta}{\theta_s}k_s \quad (2)$$

where k_s is the permeability coefficient of saturated soil, $k^{'}$, is the permeability coefficient of unsaturated soil.

$$k_s^{'}=\frac{\theta_r+\frac{(\theta_s-\theta_r)}{\left(1+\left(a_f(u_a-u_w)\right)^{n_f}\right)^{m_f}}}{\theta_s}k_s \quad (3)$$

$$s=\theta/n \quad (4)$$

where S is the saturation of soil, n is the porosity of soil.

Calculate the seepage field of tailings dam during rainfall

According to Eq. 3 and the FISH language, the permeability coefficient of saturated soil and unsaturated soil of tailings dam soil can be updated and assigned in real time. Through the flow chart (Fig. 1), the calculation of tailings dam seepage field under different rainfall patterns can be realized. And the results of numerical simulation calculation of tailings dam seepage field are shown Fig. 2, and the results of seepage field are more practically comparing with the actual situation.

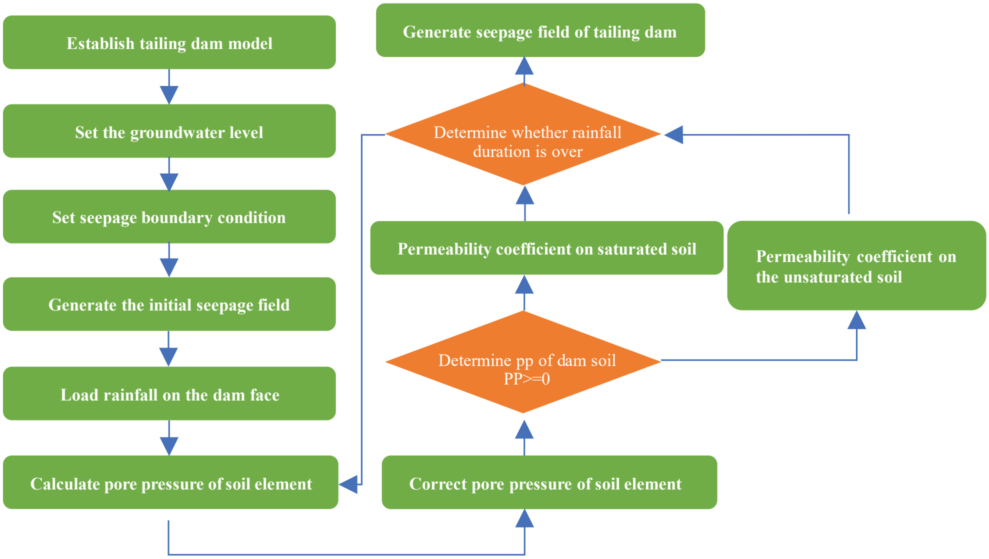

***Figure 1** Flow chart of simulation calculation of tailings dam seepage field during rainfall*

Comparison between experimental tests and numerical simulation

In order to analyse the variation law of soil moisture content on the tailings dam surface during rainfall, a tailings dam project is selected to set up rainfall monitoring points. Three sensors on surface without rod and sensors on surface with 0.2/0.7 m rod are set at the tailings dam surface. The three sensors on surface without rod are named point 1, point 2 and point 3 respectively (Fig. 3).

Select the soil of the research object tailings dam project for moisture content and permeability test. The test results are shown in the Fig. 4 and select the soil of research object tailings dam for moisture

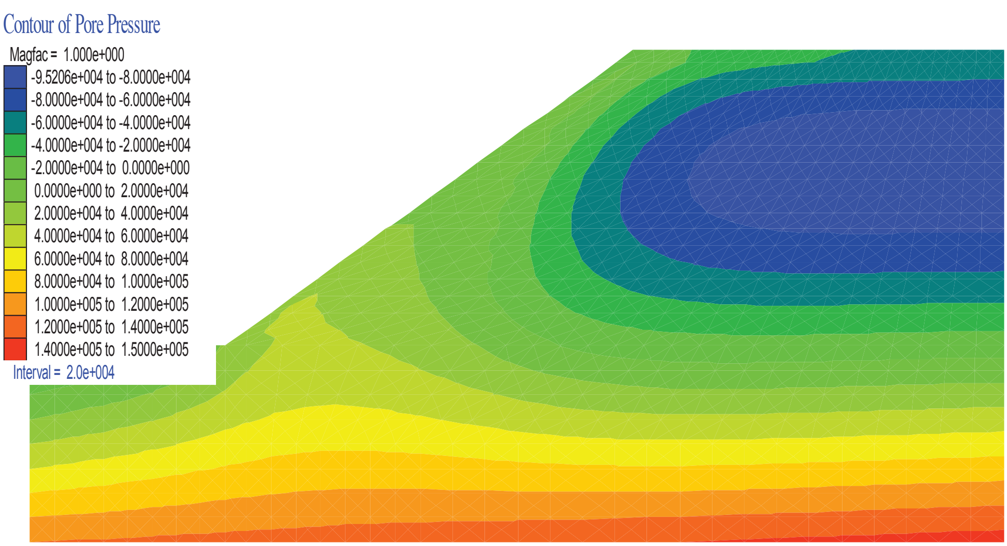

***Figure 2** PP Cloud chart of tailings dam during rainfall*

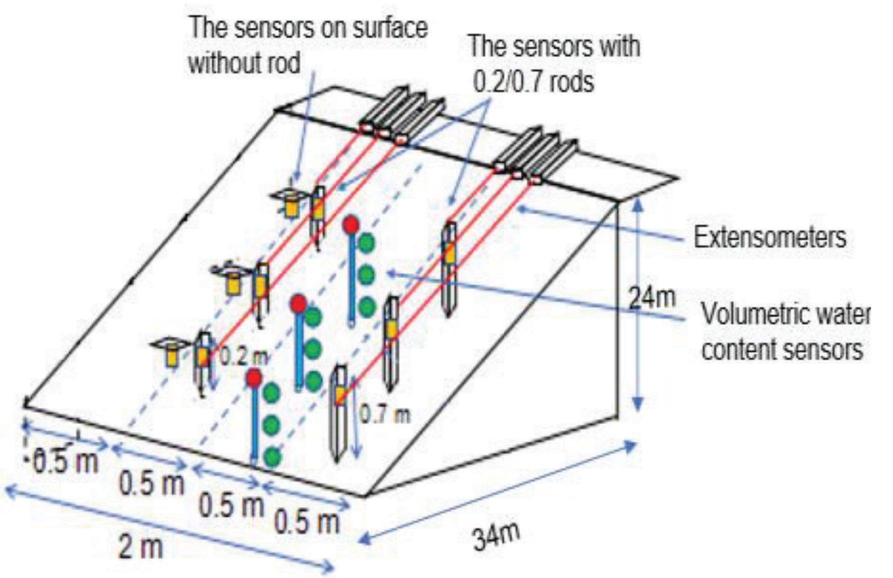

***Figure 3** Schematic diagram of tailings dam monitoring points*

content and permeability test. Fig. 4 shows that the residual moisture content of the soil is between 23% and 25%, the saturated moisture content is 44.9%.

According to experimental data and the relationship matrix suction and moisture content in the soil, the soil water characteristic curve of the soil (Fig. 5) is fitted and drawn by using Origin Software based on van Genuchten formula (Eq. 1). The relevant parameters of soil water characteristic curve are determined. By fitting the relevant parameters, the parameters values are α = 0.01445, n = 1.66746.

In practical engineering, rainfall patterns mainly include long-term continuous weak

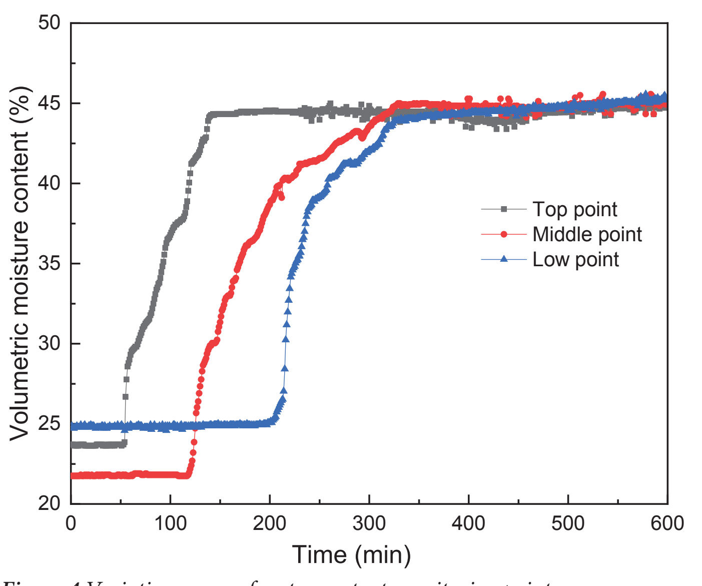

***Figure 4** Variation curve of water content monitoring points*

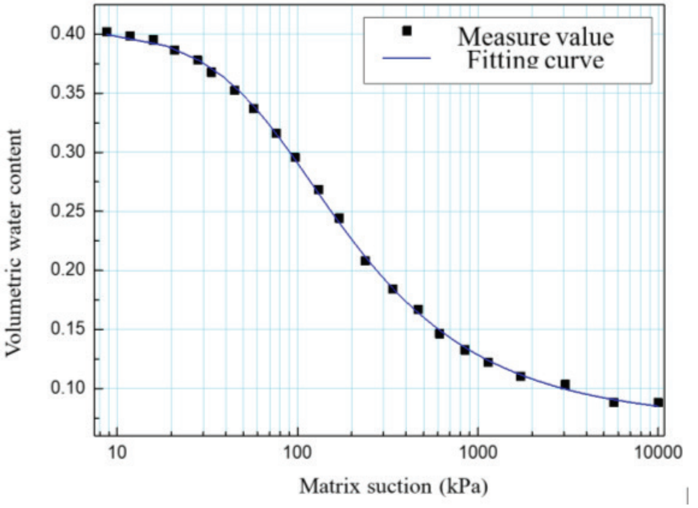

Figure 5 *Diagram of soil water characteristic curve*

rainfall and short-term periodic heavy rainfall. In order to analyze the safety and stability of tailings dam engineering under different rainfall patterns, two rainfall patterns were formulated in this paper. Pattern1 refers to long-term continuous weak rainfall; Pattern2 sustained heavy rainfall for a short time. The intermittent process of periodic heavy rainfall means no rainfall or small rainfall. The specific rainfall intensity and duration of these rainfall patterns is shown in the Tab. 2. The rainfall density of weak rainfall is 8 mm/h, the heavy rainfall is 16 mm/h, the calculation duration is 8 h, and the total rainfall is 128 mm.

For the purpose of verify the accuracy during numerical simulation program, the field test and numerical simulation monitoring point data are compared and analyzed. According to the actual situation of tailings dam engineering in field test, the corresponding numerical simulation calculation model (Fig. 6 left) is established. The groundwater level is 12 m and 15 m from the bottom of the left and right sides of the model respectively. The physical and mechanical parameters and SWCC parameters of tailings dam rock and soil mass are shown in the Tab. 2. According to the numerical simulation calculation program and the loading mode of rainfall pattern in Section 2.2, the initial seepage field (Fig. 7 center) of the tailings dam is calculated.

During the rainy season, tailings dam instability often occurs. In order to analyze the effects of different rainfall patterns on tailings dam stability, five rainfall patterns in the Tab. 2 are selected and loaded on the tailings dam surface respectively. Record the actual pore pressure of the tailings dam every 0.5 h during the rainfall. According to the actual pore pressure, the saturation degree of the soil inside the tailings dam was judge. The gravity of the saturated soil is slightly greater than that of the unsaturated soil (Eq. 5). In addition, the shear strength of the tailings dam soil is also affected by the saturation degree of the soil (Eq. 6).

$$w_s = w_d + n \times w \qquad (5)$$

Table 1 *Rainfall patterns*

Time/h	Pattern 1	Pattern 2
1	8	16
2	8	16
3	8	16
4	8	16
5	8	–
6	8	–
7	8	–
8	8	–

***Table 2** Physical and mechanical parameters and SWCC fitting parameters*

Geotechnical type	Value
Density, $kN·m^{-3}$	20
Poisson's ratio	0.28
Elastic modulus, GPa	0.2
Cohesion, kPa	35
Internal friction angle, °	20
Saturated permeability coefficient	1.73×10^{-6}
void ratio	0.3
SWCC	θr:23.7%; θs:45.9%; a_f:0.01445; n_f:1.667; m_f:0.4

Where w_s is gravity of saturated soil, n is porosity of soil, w_w is gravity of water;

$$\tau_f = c + (\sigma - \mu_a)\tan\varphi + (\mu_a - \mu_w)\tan\varphi^b \quad (6)$$

Where τ_f is Shear strength of unsaturated soil, c is cohesion of the soil, φ is internal friction angle, φbis contribution of matrix suction to friction free angle.

According to the change of pore pressure in the tailings dam, the gravity and shear strength of rock-soil mass are updated in real time by using the FISH language. The factor of safety (FOS) values of the tailings dam at different time nodes under different rainfall patterns are calculated and analyzed, and whether the tailings dam is in an unstable state is determined by the FOS values. Fig. 7 shows the variation law of tailings dam safety factor under the action of rainfall pattern 1 and under the action of rainfall pattern 2.

In the process of continuous rainfall (pattern1 rainfall pattern), with the increase of rainfall duration, the safety factor of tailings dam decreases continuously in a linear manner, and the FOS is lower than 1.20 after 6 hours of rainfall, that is to say, the tailings dam is in an unstable state. The FOS data of pattern 1 (long-term weak rainfall) and pattern 2 (short-term heavy rainfall) are selected to analyse the effects of short-term heavy rainfall and long-term weak rainfall on tailings dam safety and stability. The results show that the decline rate of tailings dam safety factor in pattern 1 (long-time weak rainfall) mode is slower than that in pattern 2 (short-time heavy rainfall) during the first 4 h of rainfall. The FOS of tailings dam decreases from 1.28 to 1.23 for the rainfall of pattern 1, and the FOS of tailings dam decreases from 1.28 to 1.21 for the rainfall of pattern 2. In the second 4h stage of rainfall, due to the continuous rainfall of the pattern 1, the FOS of the tailings dam continued to decrease. At the end of rainfall pattern 1, the FOS decreased to 1.17, and the tailings dam was in an unstable state at this time. Pattern 2 without rain at this stage, the value of tailings dam safety factor is basically unchanged. In conclusion, long-term weak rainfall has a greater effect on tailings dam stability than short-term weak rainfall.

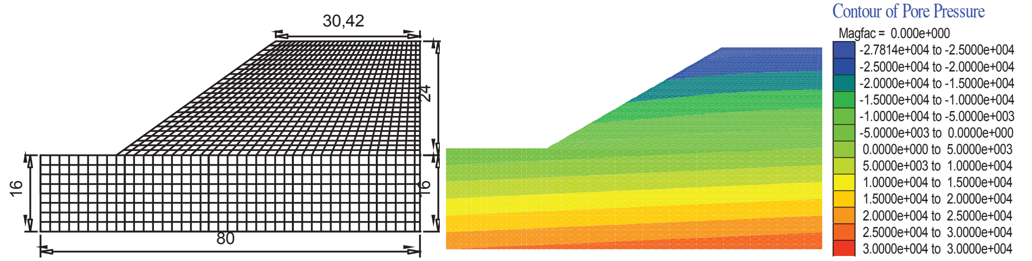

***Figure 6** Schematic diagram of numerical model (left), Initial seepage field of tailings dam before the rainfall (center and right)*

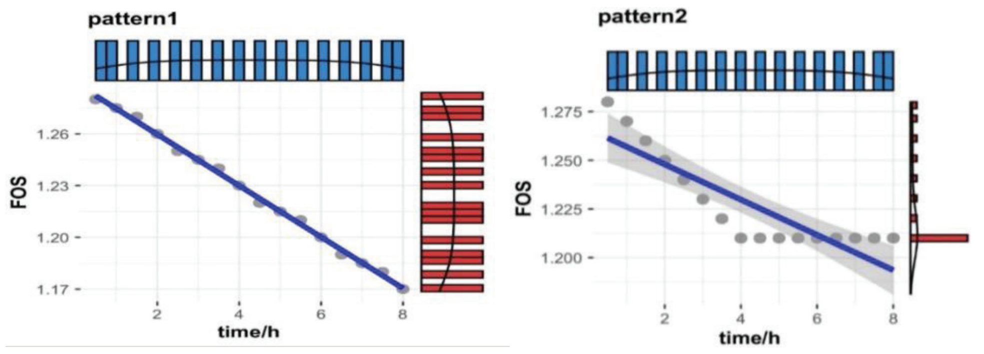

Figure 7 *FOS under rainfall pattern 1 (left), FOS under rainfall pattern 2 (right)*

Discussion and conclusions

This paper provides a method to update the permeability coefficient of unsaturated soil in real time in the process of simulating rainfall infiltration in FLAC3D, so as to calculate and analyze the variation law of tailings dam pore pressure and tailings dam stability safety factor under different rainfall patterns more accurately. The method can help researchers in the field of seepage analysis to calculate and analyse accurately the variation law of pore pressure and stability safety factor of the tailings dam under different rainfall pattern. In the study, we establish the corresponding relationship between the permeability coefficient of unsaturated soil and saturated soil, update the permeability coefficient of unsaturated soil in real time by FISH language, so as to simulate and calculate accurately the variation law of pore pressure and the FOS of tailings dam in during the rainfall infiltration. The rainfall patterns such as short-time heavy rainfall, long-time weak rainfall and periodic rainfall are loaded on the tailings dam surface, and the changes of pore pressure and FOS of the tailings dam are calculated and analysed. The results show that the long-term weak rainfall is more threatening than short-term heavy rainfall to the safety and stability of tailings dam in the same conditions of total rainfall.

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