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The Influence of Pore Air Pressure on Slope Stability Under Various Rainfall Patterns

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Abstract: *Rainfall is the most important factor to induce landslide, of which rainfall pattern is the main influence parameter. Generally, during the analysis of slope stability under different rainfall patterns, the influence of pore water pressure in saturated zone is mostly considered, while the influence of pore air pressure in unsaturated zone is seldom analyzed from the angle of water-air coupling. Based on the theory of water-air two-phase flow, this paper calculated and simulated the variation of pore air pressure changing with the rainfall time under three typical rainfall patterns (weakened, concentrated and enhanced), and combined the slope stability analysis model of considering pore air pressure to study the influence of pore air pressure on slope stability. The results show that the influence of pore air pressure on slope stability is detrimental under the three rainfall patterns. And the response duration of the pore air pressure is the longest under the weakened rainfall pattern, the concentrated pattern is the second, and the enhanced pattern is the shortest. The influence of pore air pressure on the safety factor of slope stability is the greatest under the weakened rainfall pattern, which can easily lead to the instability of the slope. Thus, we shall take the necessary engineering measures in advance in the event of such rainfall pattern prediction.*

Keywords: Rainfall Patterns; Slope Stability; Pore Air Pressure; Rainfall Infiltration; Water-air two-Phase Flow

Introduction

Rainfall is the most important factor to induce landslide, of which rainfall pattern is the main influence parameter [1]. The variation of slope seepage field under different rainfall patterns is quite different, which will affect the change of moisture content and pore pressure in slope. The increase of pore pressure is one of the key factors leading to the instability of the slope. The pore pressure in the slope can be divided into the pore water pressure in the saturated zone and the pore air pressure in the unsaturated zone [2]. The existing numerical simulation of rainfall infiltration and the test of rainfall and landslide [3-6] show that the migration of pore air in slope has an important influence on slope stability when the slope is relatively closed. In the past, the researches on the variation of pore water pressure caused by different rainfall patterns and the influence of the pore water pressure on the slope stability had been relatively mature [7-9], what's more, it is difficult to monitor and simulate the gas phase pressure and the researches on the influence of gas pressure on slope stability is relatively few in unsaturated zone under the different rainfall patterns. Therefore, based on the theory and method of water-air two-phase flow, this paper established the model of water-air two-phase flow then calculating and simulating the distribution of pore pressure in the seepage field under three different rainfall patterns (weakened, concentrated and enhanced), and combined the shear strength theory of unsaturated soil, considered slope stability analysis model of pore air pressure to study the influence of pore air pressure on slope stability.

1 Mathematical Model of Water-Air Two-Phase Flow

1.1 Basic Control Equation

The basic control equation of water-air two-phase flow contains the liquid and air flow equations, and the coupling of water-air two-phase flow is realized through the correlation of many parameters, such as matrix suction, saturation, porosity, pore pressure and so on [10]. The slope can be regarded as a porous continuous medium composed of solid, liquid and gas phases and it conforms to the law of conservation of continuous medium. The principle of conservation of mass is applied to the calculation of seepage flow in porous media so that the basic control differential equations of water and gas can be deduced, that is,

$$\phi \frac{\partial S_{\mathrm{r}}}{\partial t} + \nabla \cdot \left[-\frac{k_{\mathrm{r}}^{\mathrm{w}} k}{\mu_{\mathrm{w}}} (\nabla p_{\mathrm{w}} + \rho_{\mathrm{w}} g) \right] - \frac{Q_{\mathrm{w}}}{\rho_{\mathrm{w}}} = 0 \tag{1}$$

where S_{r} is the water saturation; ϕ is the soil porosity; k is the intrinsic permeability associated with porosity, m^2; $k_{\mathrm{r}}^{\mathrm{w}}$ is the relative water permeability; μ_{w} is the viscosity coefficient of water phase, Pa·s; p_{w} is the pore water pressure, Pa; Q_{w} is the internal source term of the liquid phase; ρ_{w} is the water density, kg / m3; g is the acceleration of gravity, N / kg.

$$-\phi \frac{\partial S_{\mathrm{r}}}{\partial t} + \nabla \cdot \left[-\frac{k_{\mathrm{r}}^{\mathrm{a}} k}{\mu_{\mathrm{a}}} (\nabla p_{\mathrm{a}} + \rho_{\mathrm{a}} g) \right] - \frac{Q_{\mathrm{a}}}{\rho_{\mathrm{a}}} = 0 \tag{2}$$

where $k_{\mathrm{r}}^{\mathrm{a}}$ is the gas relative permeability; μ_{a} is the viscosity coefficient of gas phase, Pa·s; p_{a} is the pore air pressure, Pa; Q_{a} is the internal source term of gas phase; ρ_{a} is the gas phase density, kg/m^3.

The unbalanced force exited in the interface of water and air, caused by the unequal air pressure and water pressure is called matrix suction. The expression is:

$$p_{\mathrm{c}} \equiv p_{\mathrm{a}} - p_{\mathrm{w}} \tag{3}$$

1.2 Calculation of Equation Solving

For the above water-air two-phase flow control differential equations, there are five unknown parameters in the formula, and another three constitutive relations need to be introduced. A large number of experiments and theoretical analysis show that there is a strong correlation between soil matrix suction and saturation, that is, there is a strong correlation between the soil-water characteristic curve and saturation, it is the relative permeability curve, which can be divided into aqueous relative Permeability Coefficient Curve and Gas Relative Permeability Coefficient Curve. These three relative curves are three important constitutive relations in water-air two-phase flow [11]. In this paper, the van Genuchten model [12] (Eq. (4))was used to characterize the relationship between substrate suction and saturation, the water-saturation relationship was expressed by van Genuchten-Mualem model [13] (Eq. (5)), the air-saturation relationship was expressed by van Brooks-Corey model [14] (Eq. (6)).

$$p_{\mathrm{c}} = p_0 \left[(S_{\mathrm{e}})^{-1/\lambda} - 1 \right]^{1-\lambda} \tag{4}$$

$$k_{\mathrm{r}}^{\mathrm{w}} = S_{\mathrm{e}}^{\ 0.5} \left[1 - (1 - S_{\mathrm{e}}^{\ 1/m})^m \right]^2 \tag{5}$$

$$k_{\mathrm{r}}^{\mathrm{a}} = (1 - S_{\mathrm{e}})^2 (1 - S_{\mathrm{e}}^{\ 2}) \tag{6}$$

where S_{e} is the effective water saturation, $S_{\mathrm{e}} = (S_{\mathrm{r}} - S_{\mathrm{rw}})/(1 - S_{\mathrm{rw}})$, S_{rw} is the residual saturation; p_0、λ is the parameters related to material properties; In accordance with relevant information, this calculation is taken $p_0 = 1.33$, $\lambda = 0.449$, $m = 0.9$,

$S_{rw} = 0.3$.

2 Slope Stability Calculation Considering Pore Air Pressure

2.1 Shear Strength Formula of Unsaturated Soil

For unsaturated soils, the commonly used stress state variables are the effective stress and matrix suction. The early representative single-stress state variable formula was proposed by Fredlund et al. [15] (1978).

Fredlund formula for shear strength of dual-stress state variables, which considers the shear strength of unsaturated soils composed of the effective cohesion, the net normal stress and the strength caused by the matrix suction. The net normal stress-induced strength is related to the effective internal friction angle , The intensity caused by the matrix suction is related to another angle, can be expressed as:

$$\tau_{\mathrm{f}} = c' + (\sigma - p_{\mathrm{a}})\tan\varphi' + (p_{\mathrm{a}} - p_{\mathrm{w}})\tan\varphi^{\mathrm{b}} \tag{7}$$

where τ_{f} is the shear strength; σ is the normal positive stress; c' is the effective cohesion; φ' is the effective internal friction angle; $\tan\varphi^{\mathrm{b}}$ is the shear strength increases with the substrate suction rate $(p_{\mathrm{a}} - p_{\mathrm{w}})$.

2.2 Analysis Model of Slope Stability Considering Pore Air Pressure

Rainfall infiltration of slopes and rainfall intensity are different under different rainfall patterns. When the surface of the slope is saturated, a partial sealed space is formed, and the pore air in the slope migrates with the infiltration of rainwater, resulting in the formation of pressure gradient of air to act on the slide. Due to the inhomogeneity of slope at the bottom of the landslide strip, the air pressure between the landslides cannot be neglected in accordance with the internal force of the slope. And properties of the pore air pressure and pore water pressure are the same, they can be considered in accordance with the isotropic ball pressure, and if we assumed that each soil are vertical, pore air pressure are perpendicular to the boundary direction of the soil strips, and the size of pore air pressure is equal, direction is opposite between the two soil strips, the calculated diagram of the residual thrust method considering the pore air pressure is shown in figure 1.

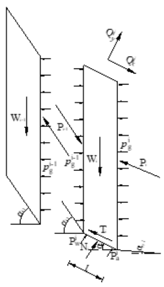

Fig 1: Residual thrust method considering the pore air pressure.

On the sliding surface, the direction of the remaining thrust is parallel to the sliding surface of the upper soil strips, and the effective normal force and tangential force meets the Fredlund shear strength criterion. For the i (i = 1, 2, …, n) soil strip, we established a local coordinate system along the parallel and perpendicular to the direction of the bottom surface of the soil strip. According to the force balance, the thrust between the soil strips is:

$$P_i = W_i \sin\alpha_i - \left[c_i l_i + \left(W_i \cos\alpha_i - p_a^i l_i\right)\tan\varphi_i + l_i\left(p_a^i - p_w^i\right)\tan\varphi^b\right] / F_s + \left(P_{i-1} + \Delta p_i\right)\psi_i \quad (8)$$

$$\psi_i = \left[\cos\left(\alpha_{i-1} - \alpha_i\right) - \frac{\tan\varphi_i}{F_s}\sin\left(\alpha_{i-1} - \alpha_i\right)\right]$$

where P_i is the remaining sliding force of the ith, that is, the thrust of the next soil strip; W_i is the gravity of ith soil strip; α_i is the slippery angle at the bottom of the ith soil strip; F_s is the current safety factor; p_a^i is the pore air pressure at the bottom surface of the ith soil strip; p_w^i is the pore water pressure at the bottom surface of the ith soil strip; c_i is the cohesion force at the bottom slip surface of the ith soil strip; l_i is the length of slippery surface at the bottom slip surface of the ith soil strip; φ_i is the internal friction angle at the bottom slip surface of the ith soil strip; ψ_i is the thrust transfer coefficient of the ith bar; Δp_i is the lateral air pressure gradient of the ith soil strip $\Delta p_i = p_g^{i-1} - p_g^i$; p_g^i is the air pressure between the ith soil strip.

When calculating the safety factor of slope stability, we shall first assume an initial value and then pushing downwards along the sliding strip from the first soil strip at the top of the slide body until the thrust of the last soil strip is deduced. When the safety factor is equal to zero, the safety factor is the required safety factor, otherwise we would repeat the above steps.

3 Analysis and Discussion of Engineering Case

3.1 Model and Program of Calculation and Analysis

The Tanjiahe landslide is located in Shazhenxi Town, Zigui County, Hubei Province. It is 56km away from the Three Gorges Dam with a landslide width of 400m, a vertical length of 1000m, an average thickness of 40m, an area of about 400,000 m2, a total volume of about 1600 × 104m3 and a main slip direction of 340 °[16]. The rainfall pattern was selected by the analysis of meteorological historical records. The average annual rainfall in the three gorges reservoir ranged from 996.7 to 1204.3mm. The maximum annual rainfall has reached 1752.6mm, and the maximum daily rainfall has reached 358.0mm. In order to make the typical rainfall process more representative and ensure that the total rainfall under different rainfall patterns and the maximum rainfall intensity is consistent, we have simulated the once-in-hundred-year rainfall in the three gorges reservoir: the total rainfall is 358.0mm and the maximum rainfall intensity is 40mm/h, continuing 24h, three typical rainfall patterns were shown in Figure 2. In this calculation model, the typical main sliding surface in Tanjiahe landslide is selected as the calculation section with the horizontal length of 1160m and the vertical height of 450m. Sub-grid in Tanjiahe landslide was shown in Figure 3.

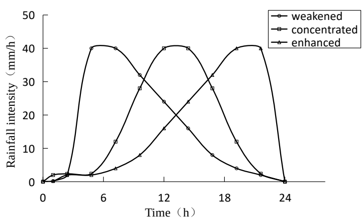

Fig.2. Three typical rainfall patterns

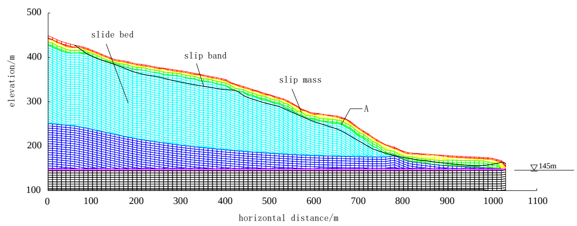

Fig.3. Sub-grid in Tanjiahe landslide

3.2 Boundary Conditions and Calculation Parameters

The boundary conditions for the calculation model are divided into the following: the lateral and bottom of the trailing edge are impervious to water; the water pressure below the water level in the leading edge of the model is the known water pressure boundary (Dirichlet boundary condition). The numerical value depends on the elevation of the water level in the reservoir (145m). When simulating rainfall infiltration process under different rainfall patterns, rainfall infiltration boundary exists above the slope in front of the model, and the rainfall infiltration boundary is the flow boundary of the known boundary element (Neumann boundary condition). In order to reduce the influence of the initial state of the slope on the analysis, the calculation is based on the initial saturated saturation of the slope to the seepage field, which is regarded as the initial condition of rainfall infiltration. When the rainfall intensity is less than the maximum infiltration rate of slope, no runoff occurs on the slope table. When the rainfall intensity is greater than the maximum infiltration rate of the slope body, the slope table produces runoff. Given that the slope head runoff is smaller than the atmospheric pressure, it can be negligible.

The main parameters involved in the calculation parameters of the landslide test data statistics, analogy and inverse calculation analysis, equation (1), (2) are $\varphi = 0.4$, $\rho_w = 1\times10^3 \text{kg/m}^3$, $\rho_a = 1.29 \text{kg/m}^3$, $g = 9.8 \text{N/kg}$, $\mu_w = 1.0\times10^{-3} \text{N}\cdot\text{s/m}^2$, $\mu_a = 1.0\times10^{-5} \text{N}\cdot\text{s/m}^2$. The main mechanical parameters are listed in table 1.

Table 1 The main mechanical parameters

layer	dry density ρ_d /g·cm^{-3}	poisson ratio μ	porosity n	saturated infiltration coefficient k_s /m·s^{-1}	The intrinsic permeability coefficient k /m^2
slip mass	1.53	0.21	0.36	1.7×10^{-5}	4.0×10^{-13}
slip bed	1.68	0.28	0.30	5.0×10^{-6}	2.0×10^{-13}

3.3 Analysis of Calculation Results

3.3.1 Water Head change of Pore Air Pressure

The maximum pore air pressure head in the weakened, concentrated and enhanced rainfall patterns was 4.40, 3.99 and 3.64m at A node, the maximum difference value is 0.76m, response duration of pore air pressure was 12.5, 10.3, 7.2 h, the maximum difference value is 5.3 h;

The weakened rainfall pattern resulted in a large amount of rainfall in the early period, thus resulting in the rapid formation of transient saturated zone on the slope. The relative permeability coefficient of the surface soil decreased to 0, and the air in the slope was hard to escape from the slope surface. In the concentrated and enhanced rainfall patterns, the air escapes from the slope before the slope expresses to the local saturation during the pre-rainfall growth, which makes the pore air pressure response duration is shorter than weakened type.

When the rainfall intensity weakened below the rainfall infiltration intensity, the slope surface changed from saturated infiltration to unsaturated infiltration, and the pore air pressure rapidly dissipated through the unsaturated seepage voids (the viscosity of the air was far less than water viscosity), the peak value of pore air pressure of slope changed after the maximum rainfall intensity, which corresponded with the actual cases.

3.3.2 Analysis of Slope Stability

The curve of the safety factor on the sliding surface under different rainfall patterns changing with time was shown Figure 5. The curve of the safety factor of slope stability considering the pore air pressure is represented by weakened Q, concentrated Q and enhanced Q respectively. The influence of pore air pressure on the safety factor of slope is the largest in the weakened rainfall patterns, followed by the concentrated and the enhanced patterns, the overall impact is the smallest. The minimum value of safety factor of slope without considering the pore air pressure in the weakened rainfall pattern is 1.25, the minimum value of the slope safety factor considering the pore air pressure reaches 1.11, which is lower than the value of safety factor reserve (F_{s0} =1.20).

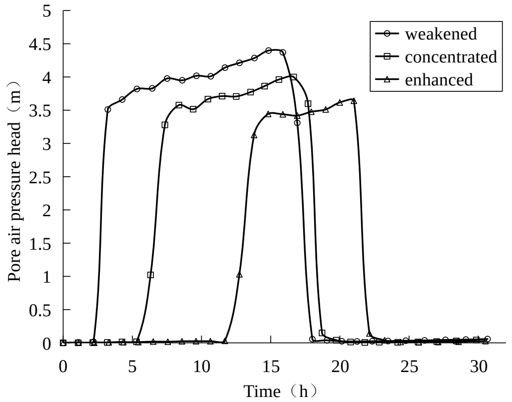

Fig.4. A node pore air pressure head

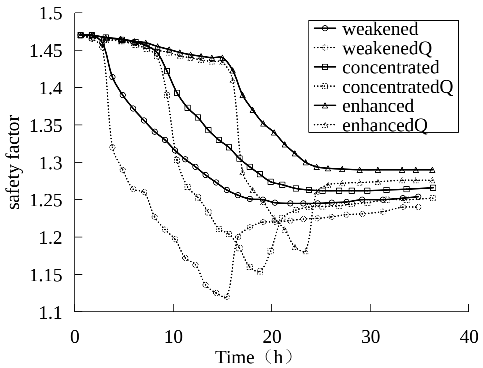

Fig.5.The curves of slope safety factor

4 Conclusion

Based on the theory and method of water-air two-phase flow method, this paper calculates the variation law of pore air pressure on the slope during rainfall infiltration and combines the shear strength theory of unsaturated soil and the slope stability analysis model considering pore air pressure. Taking landslide as an example, the influence of pore air pressure on slope stability under different rainfall patterns was simulated. The results show that: (1) The pore air pressure has an adverse influence on the slope stability under different rainfall patterns. And the influence of pore air pressure on the safety factor slope stability is the largest for the weakened rainfall pattern, followed by the concentrated and enhanced patterns. (2) The response time and the intensity of the change of the pore air pressure under the weakened rainfall patterns are the largest, followed by the concentrated and the enhanced patterns. (3) After experiencing three rainfall patterns with a total rainfall of 358mm and a duration of 24h, the stability and safety factor of the Tanjiahe landslide are all decreased. The weakened rainfall pattern was most likely to induce landslide considering the influence of pore air pressure. And if we encountered this type of rainfall pattern, the necessary engineering measures should be taken in advance (such as piling support, at the same time, embedded the vent pipe into the slope to increase the release channel of pore air, thereby reducing the influence of pore air pressure).

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