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Research Article

Study on the Seepage Mechanism of Rainwater on Granite Residual Soil Cut Slopes

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In order to study the seepage process of rainwater on granite residual soil cut slopes, a numerical model for seepage analysis of granite residual soil cut slopes was established. Then, by applying the rainfall boundary condition, the seepage path of rainwater on the slope was analyzed under the condition of rainfall infiltration. Finally, during rainwater seepage, the volumetric water content and pore-water pressure change characteristics inside the slope were analyzed, and the seepage mechanism of rainwater in the granite residual soil slope was revealed. The results show that, under the condition of rainfall infiltration, the surface area of the slope gradually forms a saturated area in a temporary stable state. As the saturated area in the temporary stable state gradually extends to the inside of the slope, the area gradually increases and a groundwater level recharge area is gradually formed at the foot of the slope. Rainwater infiltration changes the original stable state of the slope, causing the granite residual soil slope to change from the two original distribution states of the unsaturated area and saturated area to the three distribution states of the temporarily stable saturated area, unsaturated area, and saturated area from top to bottom. The volumetric moisture content of slope-monitoring points increased gradually with an increase in the duration, and the overall distribution showed an "S" shape. The infiltration of rainwater causes the pore-water pressure of the granite residual soil to increase gradually, and matric suction gradually disappears. In particular, the disappearance of the matric suction at the foot of the slope will lead to the gradual weakening of the shear strength of the slope soil, thus affecting the slope stability.

1. Introduction

Granite residual soil is a special rock and soil mass formed by long-term weathering of granite. In the world, granite residual soil is widely distributed. With the rapid development of the transportation industry, in railway and highway construction projects, in order to ensure the stability of the route, some granite residual soil is often excavated, thus forming a large number of cut-slope projects [1–3]. Granite residual soil has good compressive strength, but its cohesion is poor. Whenever the rainy season comes, the infiltration of a large amount of rainwater further weakens the cohesion of the granite residual soil, resulting in landslide disasters on the slope, which seriously affect traffic safety.

Taking the granite-disabled soil slope as the research object, domestic and foreign scholars have carried out a lot of research. In terms of engineering characteristics of granite residual soil, Tang et al. used a self-developed tensile strength tester to analyze the variation law of the tensile strength of granite residual soil with different moisture content during humidification and drying and clarified the compressive strength of granite residual soil during humidification and drying [4]. Alias et al. analyzed the variation law of shear strength of granite residual soil through a triaxial test and revealed the formation characteristics of shear strength of granite residual soil [5]. Ferreira et al. analyzed the effect of cyclic loading on the interfacial cohesion between granite residual soil and geogrids and studied the main control of the loading frequency, amplitude, and other influencing factors affecting the interfacial strength [6].

In the aspect of granite residual soil slope stability, Yang et al. studied the development and formation process of fissures in granite residual soil slopes under the condition of a dry-wet cycle and believed that the development degree of fissures in granite residual soil slopes had a positive correlation with the number of dry-wet cycles. The slope instability time has been advanced [7]. Guo et al. believed that rainfall is the key factor leading to the catastrophic occurrence of granite residual soil slopes. Therefore, the improved Mein–Larson model was used to analyze the variation law of the wetting front on the slope under the condition of rainfall infiltration [8]. By burying the moisture sensor, Fei and Qian measured the variation characteristics of matric suction and moisture content of the granite residual soil slope during rainfall. The results show that rainfall infiltration changes the distribution of matric suction on the granite residual soil slope, thus causing the slope stability to change, but this effect decreases gradually with an increase in depth [9]. Wang et al. analyzed the variation law of the wetting front on the granite residual soil slope under the condition of rainfall infiltration and proposed a slope stability analysis method considering the time-varying effect. The results show that the probability of slope failure is controlled by the position of the slip surface [10]. Wei et al. used a combination of numerical and laboratory model tests to analyze the influence of different slopes and heights of cut slopes on the slope stability under rainfall conditions, taking artificially cut slopes of granite residual soil as the research object [11]. It can be seen from the abovementioned research study that rainfall is the key factor that induces the instability of granite residual soil cut slopes. However, the existing research results are still not deep enough to study the seepage mechanism of rainwater in granite residual soil.

In view of this, this paper takes the granite residual soil cut slope as the research object, focuses on the rainfall factor, and uses numerical software to establish the seepage model of rainwater on the granite residual soil slope. The seepage evolution characteristics of the granite residual soil slope during rainwater infiltration were deeply analyzed, the seepage path of rainwater on the slope was clarified, and the seepage mechanism of rainwater on the granite residual soil slope was revealed. This study provides theoretical reference for the stability control measures of granite residual soil slopes.

2. Seepage Model of Granite Residual Soil Cut Slopes

2.1. Construction of Percolation Differential Units. Granite residual soil has certain porosity. When rainwater infiltrates into the interior of the granite residual soil slope, the flow of rainwater in the void will break the original saturated-unsaturated stable state in the slope, thereby affecting the slope stability. The migration rate of rainwater in the granite residual soil slope can be described by Darcy's law [12–14].

$$v_w = -k_w \frac{\partial h_w}{\partial y}, \tag{1}$$

where V_w is the Darcy velocity of rainwater seepage, k_w is the saturated permeability coefficient, and $\partial h_w / \partial y$ is the hydraulic gradient in a Y direction. The seepage process of rainwater in the granite residual soil slope is a complex flow process. Under normal conditions, the water flow continuity equation can be used to solve the problem by setting boundary conditions. Any tiny space unit $dxdydz$ in the granite residual soil slope is selected to establish a differential unit of rainwater seepage on the slope, as shown in Figure 1. It can be seen from Figure 1 that, in any period of time dt, the difference between the inflow and outflow of rainwater due to the action of gravity and matric suction can be expressed as the seepage flow in this period of time.

2.2. Theoretical Derivation of the Water Flow Continuity Equation. Since the granite residual soil slope is an integral structure, the seepage of rainwater on the slope is continuous. Then, according to the principle of energy conservation, the water flow continuity equation of rainwater on the granite residual soil slope can be expressed as follows [15–17]:

$$p_w\left[v_x dydz + v_y dxdz + v_z dxdy\right] - p_w\left[\left(v_x + \frac{\partial v_x}{\partial x}dx\right)dydz + \left(v_y + \frac{\partial v_y}{\partial y}dy\right)dxdz + \left(v_z + \frac{\partial v_z}{\partial z}dz\right)dxdy\right] = \frac{\partial\left(np_w dxdydz\right)}{\partial t}dt, \tag{2}$$

where n is the porosity and p_w is the density of water.

Through mathematical transformation, formula (2) can be simplified to

$$p_w \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} dxdydz = \frac{\partial\left(np_w dxdydz\right)}{\partial t}dt. \tag{3}$$

The change in water quality infiltrated into the granite residual soil is related to the compressive modulus of the granite residual soil, and the right end of formula (3) can be expressed as

$$\frac{\partial\left(np_w dxdydz\right)}{\partial t}dt = p_w\left(\frac{1}{\Gamma} + n\frac{1}{\Gamma_w}\right)\frac{\partial u}{\partial t}dxdydzdt, \tag{4}$$

where Γ is the bulk compressive modulus of the soil, Γw is the bulk compressive modulus of water, and u is the negative pore-water pressure.

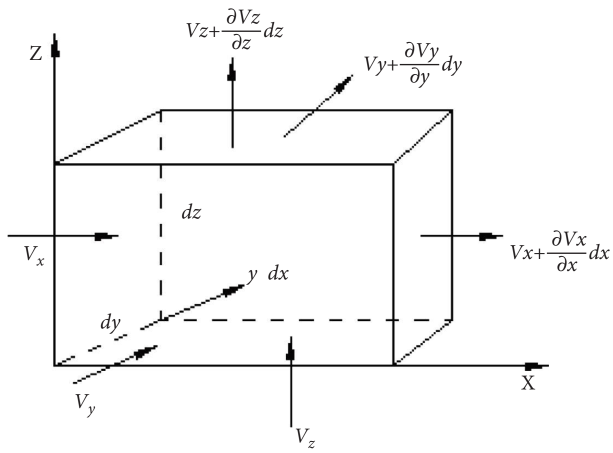

Figure 1: Percolation differential units.

The water head at the seepage differential unit of granite residual soil can be expressed as $(h - z)$so $u = \rho_w g(h - z)$. Then, there is

$$\frac{\partial u}{\partial t} = \rho_w g \frac{\partial h}{\partial t}. \quad (5)$$

In order to further simplify the seepage analysis model, this paper does not consider the anisotropy of the granite residual soil when analyzing the seepage characteristics of rainwater on the granite residual soil slope.

$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} dx\, dy\, dz = 0. \quad (6)$$

According to the water flow continuity condition, by substituting Darcy's law into formula (6), the partial differential equation of water flow continuity of rainwater on the granite residual soil slope can be obtained as follows:

$$\frac{\partial}{\partial x}\left[k_x(\theta)\frac{\partial h_w}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y(\theta)\frac{\partial h_w}{\partial y}\right] + \frac{\partial}{\partial z}\left[k_z(\theta)\frac{\partial h_w}{\partial z}\right] = 0. \quad (7)$$

2.3. Establishment of the Seepage Model. This paper takes the granite residual soil cut slope on one side of a railway as the research object and studies the seepage mechanism of rainwater on the slope. The overall excavation height of the slope was 16 m, and the excavation was divided into two levels. The height of the first-level slope was 10 m with a slope ratio of 1 : 1.75, and the height of the second-level slope was 6 m with a slope ratio of 1 : 1.5. A 2 m wide platform is set at the intersection of the two-level slopes, and the specific dimensions are shown in Figure 2. In order to simulate the groundwater level, the groundwater level elevation on the left side of the model was set to 6 m and the groundwater level on the right side was set to 3 m. In order to ensure the calculation time and accuracy, the four-node grid was used to divide the whole model into 7076 units, totaling 7286 nodes.

Reasonable boundary condition settings can accurately simulate the seepage characteristics of rainwater on the granite residual soil slope. Therefore, in the seepage numerical model, the top and the slope surface of the granite residual soil slope were set as the boundary conditions of rainfall infiltration and the road structure on the right side of the model was set as the impermeable boundary condition. Other boundaries in the numerical model of seepage were also set as impervious boundary conditions. In this paper, in order to monitor the seepage characteristics of rainwater on the granite residual soil slope, six monitoring points were set up at the top, middle, and bottom of the two-level slope at a depth of 1 m. At the same time, in order to monitor the variation law of the matric suction on the slope with the elevation, a monitoring section was set up at the top of the second-level slope.

3. Seepage Numerical Model Calculation Scheme

3.1. Physical Parameters of Granite Residual Soil. The granite residual soil slope soil samples were selected from the site, the saturated volumetric moisture content of the granite residual soil layer on the slope was measured by relevant laboratory tests to be 0.26, and the residual volumetric moisture content was 0.11. The saturated permeability coefficient was 1.91×10^{-7} cm/s. The parameters were obtained by referring to the field survey data. The specific physical parameters of granite residual soil are shown in Table 1.

The seepage of rainwater in the rock and soil body is mainly carried out through the pores between soil particles, and the size of the pores also affects the volumetric water content and matric suction of the rock and soil body. Numerous studies have shown that there is a negative relationship between the volumetric water content in rock and soil and matric suction; that is, with a gradual increase in rock-soil matric suction, the volumetric water content of soil gradually decreases. When studying the seepage mechanism of rainwater on the granite residual soil slope, the classical van Genuchten model was used to fit the curve of the volumetric water content of the granite residual soil with matric suction and the permeability coefficient with matric suction [18–20]. The fitting results are shown in Figures 3 and 4.

3.2. Slope Rainfall Program. In this paper, in order to study the seepage mechanism of rainwater on the granite residual soil slope, the rainfall grade was selected as heavy rain, the rainfall intensity was 8.7×10^{-4} mm/s, the total duration was set as 45 h, and the cumulative rainfall was 150 mm. In the seepage numerical model shown in Figure 2, slope rainfall infiltration in Table 2 was realized by applying the infiltration boundary condition.

4. Seepage Simulation Calculation Results

4.1. Slope Volumetric Water Content Distribution Law. In order to analyze the distribution law of rainwater on the slope, the cloud map of the volumetric water content of the granite residual soil slope under different rainfall times was drawn, as shown in Figure 5. As can be seen in Figure 5,

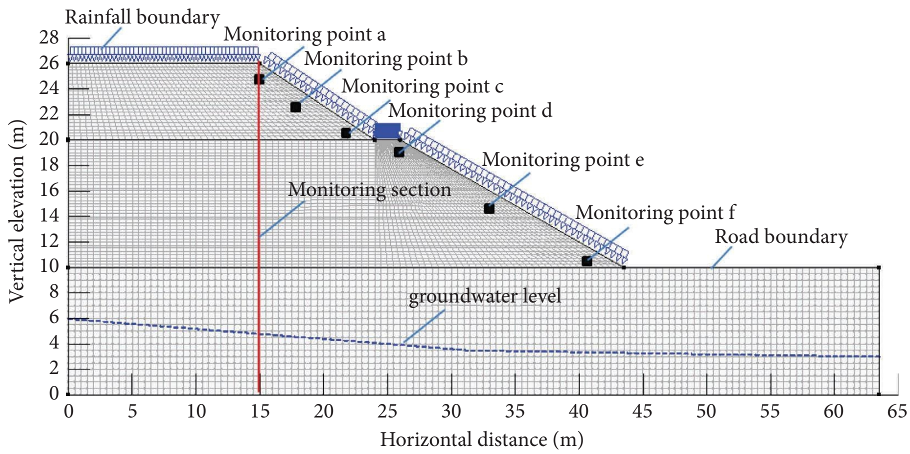

FIGURE 2: Seepage numerical model.

TABLE 1: Physical parameters of granite residual soil.

Lithology	Severe ($\gamma/(\mathrm{kN}\bullet m^{-3})$)	Saturated volume moisture content (%)	Residual volume moisture content (%)	Poisson's ratio (μ)	Permeability coefficient ($K/(cm\bullet s^{-1})$)
Granite residual soil	23	26	18	0.32	1.91×10^{-7}

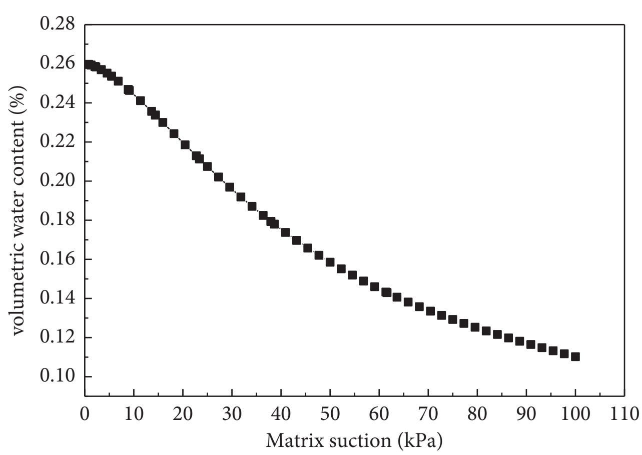

FIGURE 3: Variation curve of the volumetric water content with matric suction.

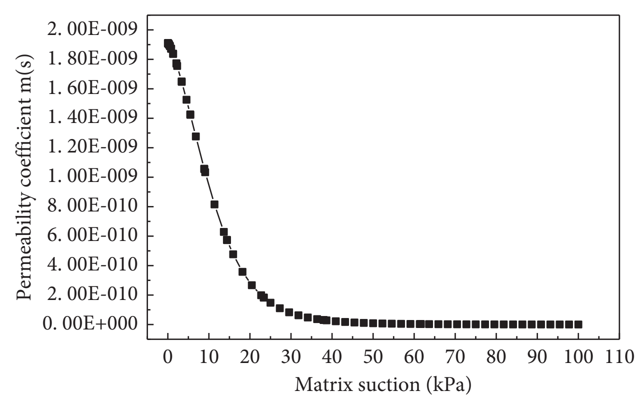

FIGURE 4: Variation curve of the permeability coefficient with matric suction.

when there is no rainfall, below the overall groundwater level of the slope is the saturated area and above the groundwater level is the unsaturated area. When rainfall reaches 6 hours, the rainwater has infiltrated from the surface of the slope to the interior of the slope. With a gradual increase in the infiltration amount, the volumetric water content of the soil in the surface area of the slope gradually increases to a saturated state, resulting in the surface soil of the slope. A transient steady-state saturation region occurs. With a gradual increase in duration, a large amount of rainwater seeps downwards inside the slope and the area of the temporary steady-state saturation area of the slope gradually increases. When rainfall reaches 24 h, a large amount of rainwater infiltrating into the inside of the slope gathers at the foot of the first-level slope and seeps down to replenish the groundwater level. When rainfall reaches 48 h, the volumetric water content at the toe of the slope reaches a saturated state, which increases the overall bulk density of the slope and weakens the shear strength of the soil at the toe of the slope.

4.2. Distribution Law of the Wet Front on Slopes. Figure 6 shows the evolution law of the wetting front on the granite residual soil slope with rainfall under the condition of rainfall infiltration. As can be seen in Figure 6, in the early stage of rainfall, with the infiltration of rainwater into the granite residual soil slope, the soil particles on the surface of the slope are gradually filled with rainwater and gradually form a critical surface with the dry soil inside the slope, that

Table 2: Rain program.

Rain level	Rainfall intensity (mm/s)	Rain duration (h)	Rain stopped (h)	Total accumulated rainfall (mm)
Rainstorm	8.7×10^{-4}	48	24	150

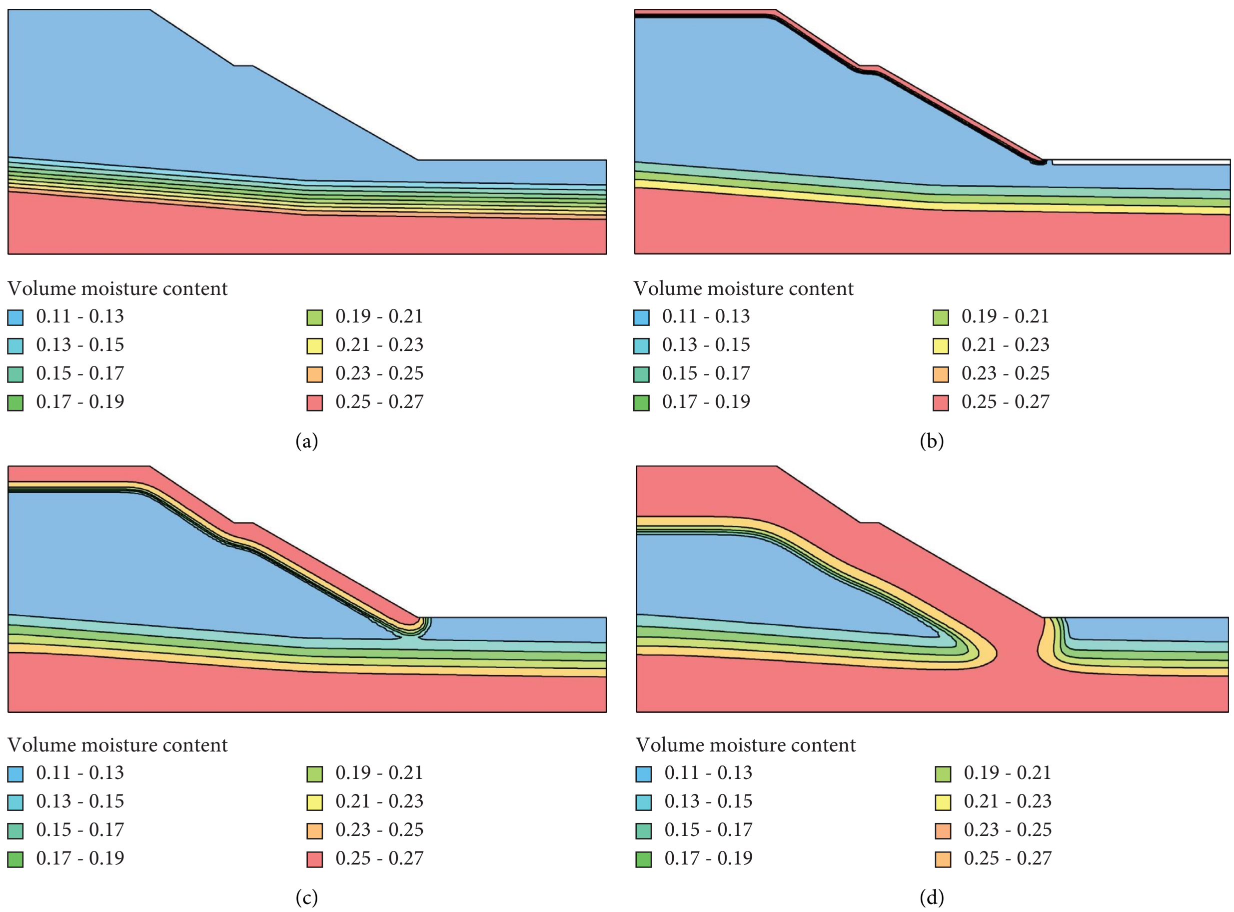

Figure 5: Slope volumetric water content distribution law. (a) Slope initial state. (b) Rain lasted 6 hours. (c) Rain lasted 24 hours. (d) Rain lasted 48 hours.

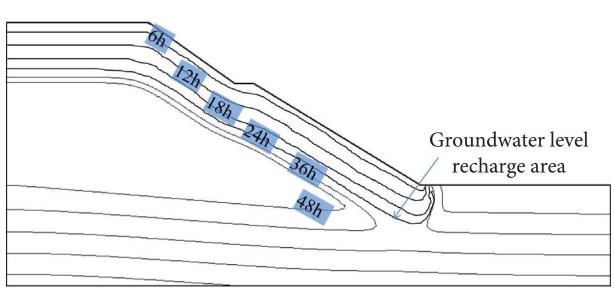

Figure 6: Distribution law of the wet front on slopes.

is, the wetting front. The overall tendency of the wetting front is distributed along the slope. With a gradual increase in duration, the wetting front gradually extends to the interior of the slope. When the amount of rainfall infiltration reaches a certain level, the wetting front curve will gradually form a concave distribution at the foot of the slope and a groundwater level recharge area will gradually be formed at the foot of the slope.

4.3. Variation Law of Volumetric Water Content at Monitoring Points. In order to analyze the variation law of the volumetric water content of the nodes on the slope under the condition of rainwater seepage from a microscopic perspective, the water content of six characteristic monitoring points was selected to analyze the seepage characteristics of rainwater on the granite residual soil slope during rainfall. Figure 7 shows the variation law of the volumetric water content of the six monitoring points of the slope under the condition of rainfall infiltration. As can be seen in Figure 7, the volumetric water content of the 6 monitoring points gradually increased to the saturated state with an increase in duration, and the overall distribution showed an “S” shape. The increase rate of the volumetric water content at the top of the two-level slope is largest, and the increase rate of the

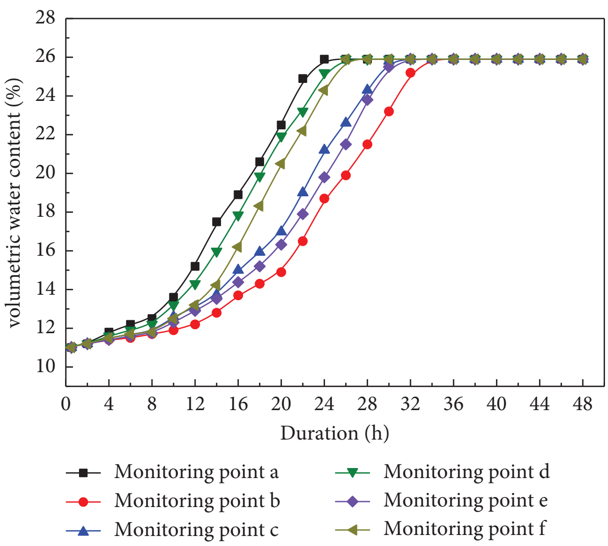

FIGURE 7: Variation law of the volumetric moisture content at monitoring points with duration.

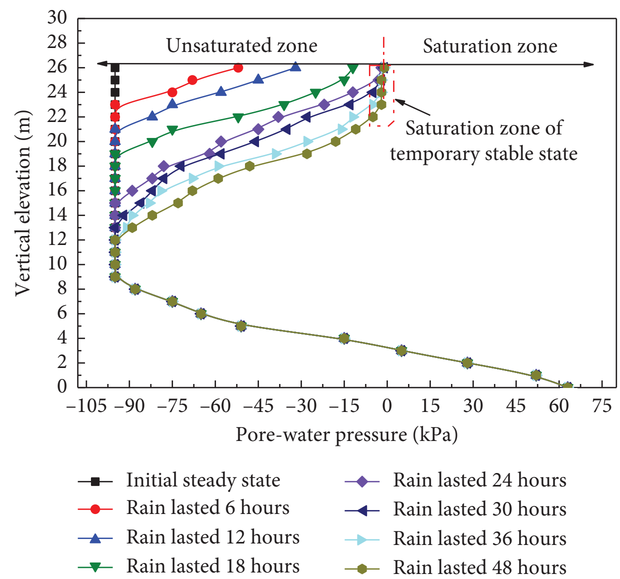

FIGURE 8: Variation law of the slope pore-water pressure with duration.

volumetric water content at the foot of the slope is smallest. The increasing rates of water content at the corresponding monitoring points on the two-level slopes are different. The increasing rates of the 6 monitored volumetric water contents are as follows: monitoring point a > monitoring point d > monitoring point f > monitoring point c > monitoring point e > monitoring point b. This is because with the continuous infiltration of rainwater on the slope surface, the pores of the granite residual soil at the monitoring points are gradually filled with rainwater and the volumetric water content gradually increases. Since the top of the second-level slope also produces rainfall infiltration, the volumetric water content of monitoring point a located at the top of the second-level slope has the highest rate of increase. Since a large amount of rainwater infiltrates at the platform, rainfall there will be greater than that of other places. Therefore, the increase rate of the volumetric water content of monitoring point d at the top of the first-level slope and below the platform is second only to that of monitoring point a. Since the rainwater on the slope is affected by the combined action of gravity and matric suction, the seepage direction will follow the slope. Therefore, the volumetric water content of monitoring point b located in the middle of the first-level slope is smallest.

4.4. Variation Law of Pore-Water Pressure. During rainfall, the pore-water pressure of a monitoring section was selected to analyze the seepage characteristics of rainwater on the granite residual soil slope. Figure 8 shows the variation law of the pore-water pressure of the monitoring section of the granite residual soil slope with the duration under the condition of rainfall infiltration. As can be seen in Figure 8, in the initial state, the pore-water pressure of the soil below the groundwater level is basically positive and the pore-water pressure of the soil above the groundwater level is basically negative. As the elevation increases, the soil pore-water pressure gradually decreases, indicating that soil matric suction gradually increases. In the early stage of rainfall, rainwater gradually infiltrated through the slope surface and the pores between soil particles at the top of the slope were gradually filled with rainwater, resulting in a gradual decrease in soil matric suction and a gradual increase in the pore-water pressure. With a gradual increase in duration, a large amount of rainwater infiltrates into the interior of the slope, resulting in a temporary stable saturation zone of the surface soil of the slope. With the continuous infiltration of rainwater, the temporarily stable saturated zone gradually extends to the interior of the slope and the area gradually increases. As a result, under the condition of rainfall infiltration, the original unsaturated area-saturated area distribution state of the slope from top to bottom evolves into a temporary stable state of the saturated area-unsaturated area-saturated area distribution state.

5. Conclusions

(1) Under the condition of rainfall infiltration, rainwater first infiltrated into the surface area of the slope and gradually formed a temporary stable saturation area in the surface area of the slope. With the continuous infiltration of rainwater, the temporarily stable saturated area gradually extends to the inside of the slope, the area gradually increases, and the groundwater level recharge area is gradually formed at the foot of the slope.

(2) Under the condition of rainwater seepage, the granite residual soil slope changes from the two original distribution states of the unsaturated area and saturated area to the temporary stable state of the saturated area and three distribution states of the unsaturated area and saturated area from top to bottom.

(3) During rainfall, the volumetric water content of the second-level slope of granite residual soil increased fastest at the top and slowest in the middle. The volumetric water content of the slope-monitoring points all increased gradually with an increase in duration, and the overall distribution showed an "S" shape.

(4) The infiltration of rainwater causes the pores of granite residual soil particles to be filled, the soil pore-water pressure gradually increases, and matric suction gradually disappears. In particular, the disappearance of the matric suction at the toe of the slope will lead to the gradual weakening of the shear strength of the slope soil, thus affecting the slope stability.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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