Research Article

The Coupling Effect of Pore Water Pressure and Pore Water Gravity in Unsaturated Soils under Rainfall Condition and Its Influence on Slope Stability

Nenghao Zhao, Haijun Lu, and Rongtang Zhang

School of Civil Engineering and Architecture, Wuhan Polytechnic University, Wuhan 430023, China

Correspondence should be addressed to Nenghao Zhao; 3560485885@qq.com

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In the study of the impact of rainfall on the unsaturated soil slope, the changes of pore water pressure and effective stress are frequently analyzed, while the loading effect caused by the change of pore water content in unsaturated soils is often neglected. In order to realize the coupling effect of the above two, a coupling model involving pore water pressure and pore water gravity was established based on the principle of seepage-stress coupling in unsaturated soils. Through a case verification, the coupling effect of pore water pressure and pore water gravity on the unsaturated soil slope was analyzed from the aspects of effective saturation, pore water pressure, effective stress, displacement, and stability. At the same time, the results were compared with those considering only the pore water pressure. The results show that the slope stability is relatively poor considering the coupling of unsaturated pore water pressure and pore water gravity. Therefore, the gravity effect of pore water in unsaturated soils cannot be neglected when calculating the stability of unsaturated soil slope under rainfall condition.

1. Introduction

Rainfall is one of the most common and dominant external dynamic factors that can induce landslides, and there are different mechanisms underlying its influence on landslides. The mechanism underlying the formation of rainfall-induced landslides can be summarized into the following five points [1–6]: (1) rainfall infiltration results in increase of pore water pressure and decrease of effective stress in rock and soil masses; (2) rainfall infiltration leads to increase of saturation and unit weight of rock and soil masses, and the slope is subject to instability and failure under the effect of gravity; (3) rainfall infiltration causes rise of underground water level and generates the uplift effect; (4) soaking in rainwater causes change of soil structure, resulting in reduction of its strength; (5) rain wash against the landslide surface leads to looseness and failure of surface rock and soil masses, which further develops toward deep in the slope, resulting in overall instability of landslide.

The quantitative theoretical research on the instability of unsaturated soil slopes is induced by rainfall mainly focuses on the interactions among pore water pressure, matric suction, and effective stress. Currently, this research is still based on the principle of effective stress presented by Terzaghi in 1923, and the effective stress equation for unsaturated soils is proposed by Bishop in 1959. On the basis of the above classical saturated-unsaturated soil mechanics, subsequent scholars improved and developed the theory and applied it in engineering issues concerning the influence of rainfall on the stability of unsaturated soil slopes. Tian et al. (2009) [7], Liu et al. (2010) [8], and Tian et al. (2016) [9] investigated the effect of rainfall on slopes under seepage-stress coupling in unsaturated soils and surface runoff-underground seepage coupling. Li et al. (2013) [10] studied the coupling process of rainfall infiltration in and the stability of inhomogeneous soil slopes; it was found that rainfall affected the shallow surface of the slope most significantly, and that rainfall seepage was concentrated in the shallow slope where the highest water permeability was observed. Li et al. (2013) [11] investigated the formation and development process of transient saturated zone in soil slopes under rainfall condition and its influence on the slope.
stability. As to the mechanism underlying the effect of saturation increase in unsaturated soil slopes on the slope stability, Ng and Shi (1998) [12] believed that the increase of pore water pressure or the decrease of matric suction led to the reduction of shear strength on the potential failure surface, thus resulting in slope instability. Ering and Babu (2016) [13] gave detailed explanation using a specific case of landslide, who also believed that the decrease of matric suction and the increase of positive pore water pressure were the main causes of slope instability. Chinese scholars Li and Zhang (2001) [14], Qi and Huang and Qi and Hu (2004, 2015) [15, 16], Wu et al. (2004) [17], Lin et al. (2009) [18], Li et al. (2016) [19] conducted quantitative researches on the mechanism underlying slope instability caused by the increase of pore water pressure and the decrease of matric suction in unsaturated soil slopes.

As can be seen from the above, current researches on the effect of rainfall on the stability of unsaturated soil slopes mainly focus on the law of change of such factors as pore water pressure, matric suction (negative value of pore water pressure in unsaturated soils) and effective stress, the interactions among these factors, and the influence of changes of these factors on the slope stability. Indeed, they are the most noteworthy issues when studying the effect of rainfall infiltration on the stability of unsaturated soil slopes. However, there is another issue that should not be ignored, i.e., the change of unit weight of unsaturated soils during rainfall. The increase of soil water pressure results in the increase of pore water gravity in unsaturated soils. In general, with the increase of saturation, the volume water content increases, which can be regarded as the loading process of the slope (Figure 1). The pore water pressure in unsaturated soils is different from that in saturated soils. The pore water pressure in saturated soils is positive and in a compressed state and is generated under the effect of gravity. The pore water pressure in unsaturated soils is negative and in a tensile state; the stress in pores mainly takes into account the matric suction, which is the difference between pore gas pressure and pore water pressure, and no consideration is given to the effect of gravity on pore water. Therefore, the research on seepage-stress coupling in unsaturated soil slopes often considers only the effect of matric suction (or positive pore water pressure) and ignores the effect of pore water gravity. For example, in literature [20, 21] involving the study of the stability of unsaturated gravel soil slopes under rainfall condition, through unidirectional coupling of seepage and stress fields, consideration is given to the effect of negative pore water pressure in unsaturated soils on the stress state of soil particles, but not to the effect of pore water gravity in unsaturated soils. Literature [22] takes into account the bidirectional coupling effect of pore pressure and stress, but only uses the pore water pressure in unsaturated soils for tensile stress calculation without considering the effect of pore water gravity.

In view of the above, this paper, focusing on the stability of unsaturated soil slopes under rainfall condition, takes into account both the change of matric suction and effective stress caused by pore water pressure in unsaturated soils and the change of soil unit weight caused by pore water gravity in unsaturated soils. On the theoretical basis of seepage-stress coupling in unsaturated soils, it considers the coupling effect of the abovementioned negative pore water pressure (matric suction) and pore water gravity. Through calculation example analysis, this paper analyzed the coupling effect of pore water pressure and pore water gravity in unsaturated soils on the slope during rainfall from five aspects, including effective saturation, pore water pressure, effective stress, displacement, and stability; and it was also compared with the case considering only the effect of pore water pressure.

2. Seepage-Stress Coupling Model for Unsaturated Soils

2.1. Seepage Continuity Equation for Unsaturated Soils. Darcy, a French engineer, proposed a theory regarding linear seepage of water in saturated soils in 1856, laying a solid foundation for the development of seepage theory of saturated media. In 1931, Richards developed Darcy’s saturated seepage theory and applied it in unsaturated seepage. The saturated-unsaturated seepage control equation for the water flow, called the Richards equation, was established quickly. The Richards equation describes the law of variably saturated seepage in porous media. With the change of saturation, when the fluid flows through the media, its hydraulic properties change; some pores are filled and some dewetted. The Richards equation discussed in this paper is based on single-phase flow, and pores between soil particles are not filled by water contain immobile air (standard atmospheric pressure). The control equation is written as

\[
\rho \left( \frac{C_m}{\rho g} + S e S \right) \frac{\partial p}{\partial t} + \nabla \cdot \left( -\frac{k_s}{\mu} \nabla p + \rho g \nabla D \right) = Q_m, \quad (1)
\]

where \(\rho\) is the pore pressure; \(S e\) is the effective saturation; \(S\) is the storage coefficient; \(C_m\) is the water capacity; \(k_s\) is the saturated permeability of media; \(\mu\) is the hydrokinetic viscosity; \(k_r\) is the relative permeability; \(\rho\) is the fluid density; \(g\) is the gravitational acceleration; \(D\) is the elevation head; \(Q_m\) is the source-sink term of seepage. Among them, \(S e, C_m, k_s\) are all determined by the Van Genuchten model in this paper.

When considering the seepage-stress coupling effect in soils, the effect of solid deformation on pore seepage should be taken into account, i.e., the equation of continuity of fluid flow in porous media under the effect of volumetric strain [23]:

\[
\rho \left( \frac{C_m}{\rho g} + S e S \right) \frac{\partial p}{\partial t} + \frac{\partial \varepsilon_v}{\partial t} + \nabla \cdot \left( -\frac{k_s}{\mu} \nabla p + \rho g \nabla D \right) = Q_m, \quad (2)
\]

where \(\varepsilon_v\) is the volumetric strain of media; \(\alpha\) is the Boit coefficient, and the value of \(\alpha\) used in this paper is 1.

The second term on the left side of Eq. (2) is the effect of soil volume deformation on pore water seepage, which is a term considering stress-seepage coupling.
2.2. Principle of Effective Stress in Unsaturated Soils. An unsaturated soil is considered to be a three-phase material system consisting of solid, liquid, and gas, where the relative quantity of pore gas phase and pore water phase and the corresponding pressure directly affect the stress state between soil particles, further influencing the macroscopic mechanical behavior of soils. When soils are saturated and the pore water pressure is in a compressed state (the pore water pressure at this moment is generated under the effect of gravity), the water pressure will reduce the effective stress in soils. When soils are unsaturated, the water in pores may exhibit high negative pore pressure (the pore water pressure at this moment does not consider the effect of gravity), and the tension stress generated will result in the increase of effective stress between soil particles. Several extended forms of the classical effective stress equation presented by Terzaghi can describe the applied stress among unsaturated soil particles; one of them is the following effective stress equation for unsaturated soils proposed by Bishop in 1959:

\[
\sigma' = (\sigma - u_a) + \chi(u_a - u_w),
\]

where \(\sigma'\) is the effective stress between soil particles; \(\sigma\) is the total stress; \(u_a\) is the pore gas pressure (since \(u_w\) is set to be a standard atmospheric pressure in this paper, \(u_a = 0\)); \(u_w\) is the pore water pressure; \(u_a - u_w\) is the matric suction; \(\chi\) is the effective stress parameter, and the value of which depends on the soil saturation and is simplified to 1 in this paper.

2.3. Stress Control Equation for Unsaturated Soils. Considering unsaturated soils as continuous porous media, the stress equilibrium equation for soils can be expressed as follows based on static equilibrium:

\[
\sigma_{ij} + F_i = 0.
\]

When soil pores are filled by water, the pore pressure will reduce the effective stress between soil particles. That is to say, in unsaturated state, the increase of pore water pressure will result in decrease of matric suction, thus reducing the effective stress; in saturated state, the increase of pore water pressure will directly result in decrease of effective stress between particles. Therefore, the constitutive equation for soils under the effect of pore water pressure is written as [24]

\[
\sigma'_{ij} = D_{ijkl}\varepsilon_{kl} - \alpha p \delta_{ij}.
\]

The second term on the right side of Eq. (5) is the effect of pore water pressure on the effective stress in soils, which means that the seepage-stress coupling effect is considered. The geometric equation is expressed as

\[
\varepsilon_{ij} = \frac{1}{2} (u_{ij} + u_{ji}).
\]

In Eqs. (4)–(6), \(\sigma_{ij}\) is the stress tensor; \(\sigma'_{ij}\) is the effective stress tensor; \(F_i\) is the body force; \(D_{ijkl}\) is the elastic tensor; \(p\) is the pore water pressure; \(\delta_{ij}\) is the Kronecker symbol (when \(i = j, \delta_{ij} = 1\); when \(i \neq j, \delta_{ij} = 0\)); \(\varepsilon_{ij}\) is the strain tensor; \(u_i\) is the solid displacement.

The above equations describe the effect of porous seepage on the stress state in saturated-unsaturated soils from the change of effective stress between soil particles caused by the change of pore water pressure. However, as far as the transient seepage in unsaturated soils is concerned, since the soil saturation changes with the seepage, the unit weight of unsaturated soils also changes accordingly (i.e., the effect of pore water gravity is considered) instead of having a fixed value like dry or wet unit weight. This is particularly important for analyzing the stability of unsaturated soil slopes under the effect of rainfall infiltration. This effect is reflected in the body force \(F_i\). The unit weight of unsaturated soils can be expressed as

\[
\gamma = \gamma_s + \gamma_w \cdot n \cdot Se,
\]
where \( y_d \) is the unit weight of dry soils; \( y_w \) is the unit weight of water; \( n \) is the soil porosity; \( S_e \) is the pore saturation.

The saturation \( S_e \) is determined based on the saturation change equation in the Van Genuchten model which is written as

\[
S_e = \begin{cases} 
\frac{1}{1 + \left|m n H_p \right|^{1/m}}, & H_p < 0, \\
1, & H_p \geq 0,
\end{cases}
\]

where \( m \), \( n \), and \( m \) are all parameters of the Van Genuchten model, where \( n = 1/(1 - m) \); \( H_p \) is the pressure head.

Equations (2), (4), (5), and (7) above take into account the effect of pore water pressure and pore water gravity on unsaturated soils, which means the coupling of pore water pressure and pore water gravity on unsaturated soils is realized on the premise that seepage-stress coupling is considered.

3. Calculation Example Analysis

3.1. Calculation Model. In order to investigate the influence that the coupling effect of pore water pressure and pore water gravity under rainfall condition has on unsaturated soil slopes, a calculation example model for unsaturated soil slopes was designed in this research, as shown in Figure 2. The slope model was 53.8 m wide at the bottom and 30 m high; the slope top was 20 m wide and the slope gradient 40°. Taking the top and surface of this slope as the rainfall boundary, the rainfall was designed to last for 5 days at the intensity of 50 mm/d, and it was assumed that the rainfall completely infiltrated into soils and other boundaries were free from seepage. The initial phreatic water level at the slope toe was 10 m; above the phreatic water level was the saturated zone, and below it was the unsaturated zone. In the unsaturated zone, the initial pore water pressure was set to -10 kPa.

In terms of seepage, this slope model was assumed to be a porous homogeneous soil slope and employed Richards’ unsaturated seepage constitutive equation (Eq. (2)). The curves of permeability function and soil water characteristic, as shown in Figures 3 and 4, respectively, were obtained by fitting the Van Genuchten retention function model; relevant parameters are given in Table 1. As to solid mechanics, the model was designed with a fixed bottom and roller supporting boundaries on both sides. An elastic-plastic constitutive model was employed for the materials of the model; the plastic part followed the Drucker-Prager yield criterion and was also associated with the Mohr-Coulomb strength parameters. See Table 1 for the specific physical mechanics parameters.

Comsol Multiphysics was used in this paper for numerical calculation of the model. For finite element meshing of the model, four monitoring points A, B, C, and D were, respectively, taken, as shown in Figure 2, to monitor pore water pressure, effective stress, and law of displacement change in the slope during rainfall.

3.2. Calculation Method. The case where the coupling effect of pore water pressure and pore water gravity in unsaturated soils was compared with the case considering only the pore water pressure (matric suction) in unsaturated soils. The modeling process consists of three steps:

1. Calculate the initial pore pressure and stress state of the model before rainfall
2. Calculate the law of change of variables such as slope saturation, pore water pressure, stress distribution, and displacement during 5 days of rainfall at the intensity of 50 mm/d; the initial pore pressure and stress used in this step were from the results of calculation in step (1)
3. Calculate the stability by the strength reduction method; the initial pore pressure and stress used in this step were from the results obtained after 5 days of rainfall in step (2)

3.3. Analysis of Calculated Results. As the rainfall continues, the saturation of unsaturated soils in the slope will change, resulting in change of pore water pressure and further changing the stress field in the slope and the displacement field; this will affect the slope stability. Therefore, this paper analyzed the coupling effect of pore water pressure and pore water gravity in unsaturated soils on the slope during rainfall from five aspects, including effective saturation, pore water pressure, effective stress, displacement, and stability; and it was also compared with the case considering only the pore water pressure.

3.3.1. Effective Saturation. The change of effective saturation of soils in the slope, taking into account the coupling effect of pore water pressure and pore water gravity, is shown in Figures 5(a)–5(f). Before rainfall (day 0), i.e., when the model is in its initial state, soils below the level of slope toe were saturated and affected by the matric suction; soils within approx. 1 m above the level of slope toe were also saturated, while soils below this height were all unsaturated; the lowest saturation was observed at the position close to the slope surface with the value being 0.35 or so; the saturation of soils in the slope was about 0.6. With the continuation of rainfall, the saturation of soils at the toe and surface of the slope gradually increased, and the thickness of nearly saturated soils close to the slope surface also exhibited gradual increase. After 5 days of rainfall, soils within 1 m away from the slope surface became nearly saturated; especially, the saturation of soils at the slope toe increased significantly. In this process, the saturation of soils deep in the slope showed no significant change. From the change of saturation throughout the rainfall duration, it is not hard to see that the significant increase of the saturation of surface soils led to a larger infiltration coefficient than soils deep in the slope, and as a result, the rainwater mainly infiltrated along soils at the shallow surface of the slope to the toe.

3.3.2. Change of Pore Water Pressure. The change of soil saturation leads to the change of pore water pressure.
Figures 6(a) and 6(b) show the contours of pore water pressure in the slope before rainfall and after 5 days of continuous rainfall, respectively. Similar to the law of saturation change, the pore water pressure in soils at the shallow surface and the toe of the slope increased significantly, and the most prominent change was observed at the slope toe; the pore pressure deep in the slope had no significant change and remained positive. In order to further analyze the law of change of pore water pressure deep in the slope throughout the rainfall duration, the curves of change of pore pressure over time at the monitoring points A, B, C, and D (see Figure 2), respectively, located at the shoulder, middle of surface, toe of, and deep in the slope were plotted, as shown in Figure 7. As can be seen from Figure 7, the pore pressure at the slope toe (point C) was positive, suggesting that soils at this point were saturated, and the most prominent increase of pore water pressure was observed at this point; soils at the other three points were all unsaturated, and the pore pressure at the shoulder (point A) and middle of surface (point B) of the slope also increased to some extent while the pore pressure deep in the slope (point D) basically had no change. The above has also verified the characteristic that the rainwater mainly infiltrated along soils at the shallow surface of the slope to the toe in the designed rainfall process.

3.3.3. Effective Stress. In this slope model, the effective stress between soil particles is mainly affected by two factors: one is that the change of pore water pressure between particles will change the effective stress at the contact point between particles; the other is that the change of pore water pressure in overlying soils will result in the change of unit weight of overlying soils, which means the total stress in underlying soils changes, resulting in the change of effective stress. Therefore, the soil slope model under rainfall condition should take into account the combined influence of the above two factors.

Figures 8 and 9 compare the distribution and change of effective stress deep in the slope between the case considering the coupling effect of pore water pressure and pore water gravity and the case considering only the effect of pore water pressure. Figures 8(a) and 8(b) show the contour maps of effective stress distribution after 5 days of continuous rainfall. As can be seen from comparison between Figures 8(a) and 8(b), the effective stress in the former case was significantly greater than that in the latter case, and it was particularly obvious in the saturated zone; in the unsaturated zone, especially near the toe and surface of the slope, the effective stress in soils in the case considering the coupling effect was slightly greater than that in the case considering only the effect of pore water pressure. Figures 9(a)–9(d) are, respectively, the curves of effective stress variation at the four monitoring points with rainfall time in the two cases. On the whole, the effective stresses at the four monitoring points exhibited a basically consistent trend of change in the two cases. The effective stress at the shoulder (point A) and middle of surface (point B) of the slope showed an overall trend of increase with the rainfall. The effective stress at the slope toe (point C) gradually decreased as the rainfall continued since soils at this point were saturated. Deep in the slope (point D), the biggest difference in effective stress was observed between the two cases; in the former case, the effective stress increased rapidly after short-duration and then showed a trend of slow increase, while in the latter
case, the effective stress increased rapidly after short-duration rainfall and then showed a trend of slow decrease. The above suggests that the effective stress deep in the slope in the case considering the coupling effect of pore water pressure and pore water gravity is greatly different from that in the case considering only the pore water pressure; such difference can be directly reflected in issues concerning slope deformation and stability.

### 3.3.4 Displacement Field

Figure 10 shows the characteristics of displacement variation at each monitoring point of the slope, which compares the curves of displacement variation at each monitoring point with rainfall time in the two cases. According to the calculated results, continuous rainfall resulted in different degrees of settlement deformation of displacement at each monitoring point of the slope; the greatest deformation was found at the slope top, and the

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**Table 1: Permeability parameters and physical mechanics parameters of slope model.**

<table>
<thead>
<tr>
<th>Permeability parameters</th>
<th>Saturated infiltration coefficient (m/s)</th>
<th>Saturated volumetric water content (m³/m³)</th>
<th>Residual volumetric water content (m³/m³)</th>
<th>Storage coefficient (Pa⁻¹)</th>
<th>Parameters of Van Genuchten model α (m⁻¹)</th>
<th>n</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1E-6</td>
<td>0.5</td>
<td>0.04</td>
<td>5.2E-9</td>
<td>1.35</td>
<td>2</td>
<td>1.3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Physical mechanics parameters</th>
<th>Dry density of soils (kg/m³)</th>
<th>Young’s modulus (kPa)</th>
<th>Poisson’s ratio</th>
<th>Cohesion (kPa)</th>
<th>Internal friction angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1800</td>
<td>1E5</td>
<td>0.3</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>

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**Figure 5:** Effective saturation varies with rainfall time (coupling case).
settlement deformation increased rapidly at the beginning of rainfall and then exhibited slow increase. Besides, the slope deformation in the case considering the coupling effect of pore water pressure and pore water gravity is greater than that in the case considering only the effect of pore water pressure.

3.3.5. Stability Analysis. The strength reduction method was used in this paper to calculate the slope stability factor after continuous rainfall in the two cases. Essentially, the strength reduction method gradually decreases $c$ and $\phi$ of materials, which results in failure of the stress of a certain element to match the strength; and the unbearable stress will gradually transfer to surrounding soil elements; when a continuous sliding surface appears (the yield points are connected to form a continuous surface), the soil slope will become instable [25].

The shear strength parameters after reduction can be expressed as

$$c_m = \frac{c}{F_r}$$  \hspace{1cm} (9)
$$\phi_m = \arctan \left( \frac{\tan \phi}{F_r} \right)$$  \hspace{1cm} (10)

where $c$ and $\phi$ are the shear strength that can be provided by soils, as listed in Table 1; $c_m$ and $\phi_m$ are shear strength necessary for maintaining equilibrium or actually developed by soils; $F_r$ is the strength reduction factor.

In Comsol Multiphysics, the parameter sweep method can be used to quickly calculate the influence of different parameter values on the calculated results. Based on this principle, the strength parameters $c$ and $\phi$ of slope soils were reduced with different factors $F_r$; then, parameter sweep was performed; the slope stability factor $F_s$ was determined based on the convergence condition of numerical calculation. The calculated results are shown in Figure 11. After 5 days of continuous rainfall, the slope stability factor in the case considering the coupling effect of pore water pressure and pore water gravity is $F_s = 1.01$, while that in the case considering only the effect of pore water pressure is $F_s = 1.09$. Besides, from the plastic strain at the time of failure,
Figure 9: Comparison of effective stress at each monitoring point varying with rainfall time in two cases.

Figure 10: Comparison of displacement at each monitoring point varying with rainfall time in two cases.

Figure 11: The stability factor and corresponding equivalent plastic strain after 5 days of rainfall. (a) Case considering the coupling effect of pore water pressure and pore water gravity. (b) Case considering only the effect of pore water pressure.
there must be great plastic deformation on the sliding surface to cause overall instability and failure of the slope in the latter case, while slight plastic deformation on the sliding surface can cause overall continuation of the sliding surface and further result in overall instability and failure of the slope in the former case. Thus, it can be seen that the pore water gravity in unsaturated soil slopes can affect the slope stability significantly, therefore, should not be ignored.

4. Conclusions

In this paper, the effects of pore water on the stability of unsaturated soil slopes under rainfall conditions are studied from two aspects: pore water pressure changes the effective stress between soil particles, and pore water gravity changes the bulk density of soil. The seepage-stress coupling model for unsaturated soils was modified to realize the coupling effect of pore water pressure and pore water gravity on unsaturated soils. The modified coupling mathematic model was applied in the design case to analyze the coupling effect of pore water pressure and pore water gravity on unsaturated soils. It was also compared with the case considering only the effect of pore water pressure. The following conclusions have been drawn from the above:

(1) For the unsaturated soil slope under rainfall condition, the changes of saturation, pore water pressure, and effective stress at the shallow surface were all more significant than those deep in the slope. The increase of the saturation of shallow surface soils led to increase of soil unit weight, which was equivalent to the application of load to the slope. Therefore, when considering the stability of unsaturated soil slopes under rainfall condition, the effect of pore water gravity in unsaturated soils should not be ignored.

(2) Through comparison between the case considering the effect of pore water pressure and pore water gravity in unsaturated soils and the case considering only the effect of pore water pressure, it can be seen that the slope stability is lower in the first case. In this calculation example, the stability factor of the slope model is $F_s = 1.01$ in the first case and $F_s = 1.09$ in the second case, which means the slope is more likely to have overall instability and failure when considering the coupling effect of pore water pressure and pore water gravity.

Data Availability

Data related to this article can be obtained through this link: https://pan.baidu.com/s/1n9i948vMiOlI8vXw097mRW?pwd=1p4e.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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