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Study on the Spatial and Temporal Distribution Characteristics of Water Migration in Expansive Soil Slope Under Rainfall Conditions

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Abstract

In order to study the temporal and spatial distribution of moisture migration of expansive soil slopes by rainfall, the FISH language programming program based on FLAC3D software introduces expansion deformation into the fluid-solid coupling model, and proposes a multi-field coupling analysis method of expansion-seepage-stress. Through the establishment of a numerical model of expansive soil slopes, the change process of rainwater infiltration of expansive soil slopes under rainfall conditions was reproduced, the change law of pore water pressure under different rainfall durations was studied, and the influence of swelling deformation on the seepage process was explored. Studies have shown that the pore water pressure presents a slow-increase-slow trend. Expansion deformation has an inhibitory effect on the water migration of the slope, and the time lag of the decrease in the infiltration depth, the distribution of the transient saturation zone, and the development of the wet front affected by the expansion deformation is prolonged.

Keywords

Road Engineering; Rainfall Infiltration; Expansive Soil Slope; Water Migration.

1. Introduction

With the development of China's western region in full swing, road construction gradually extends to mountainous areas, inevitably encountering special engineering geology such as expansive soil. There are more and more engineering problems caused by expansive soil. Among them, geological disasters such as collapse and landslide of expansive soil slope induced by rainfall infiltration are urgent engineering problems to be solved [1]. A large number of investigations [2-4] indicate that rainfall infiltration may be the main factor inducing the instability of expansive soil slopes. The change of humidity field caused by rainfall infiltration is a typical unsaturated infiltration process, with the temporal and spatial evolution of rainfall infiltration, the pore water pressure and water content in the slope change drastically, which causes the reduction of matrix suction and shear strength, and then formation of transient saturation zone. It increases weight of the soil in this area is not good for the stability of the slope. In addition, after absorbing water, the expansive soil will have undesirable properties such as strain softening and swelling deformation, which accelerates the slope failure. Therefore, it is very important to grasp the temporal and spatial distribution characteristics of water infiltration in expansive soil slopes.

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In order to analyze the unsaturated seepage process of expansive soil slopes under rainfall conditions, the numerical simulation method has become an important method for the majority of researchers to analyze unsaturated infiltration due to its easy data extraction, intuitiveness and repeatability. Many scholars [5-7] used the non-coupling method of stress and seepage to analyze the seepage process of expansive soil slopes from rainfall intensity, rainfall duration, pore water pressure and temporal and spatial distribution of transient saturation zone. However, a complete standard has not yet been established to describe the changes in the transient saturation zone under different rainfall conditions, and the above method does not consider the influence of pore water and soil skeleton by soil deformation, resulting in water migration process and seepage process different from the actual. In recent years, the FLAC^{3D} software based on the finite difference method has become the main method for many researchers to solve the problem of unsaturated soil seepage-stress coupling due to its mature saturated soil fluid-solid coupling analysis module. Wang [8] made the simulated rainfall infiltration process more close to reality by imposing a dynamic flow boundary, and solved the initial pore water pressure distribution problem. Jiang [9] used the built-in FISH language to improve its unsaturated infiltration calculation function, and provided a numerical method for the rainfall infiltration problem of unsaturated soil slopes. Qin [10] used FLAC^{3D} software to establish a two-dimensional slope model, adopted the strength reduction method, compared the stability of the slope with or without rainfall, and concluded that the safety factor of stability under rainfall conditions decreased significantly. Yang [11] analyzed the rainfall infiltration of unsaturated slopes based on the FISH voice programming built in FLAC^{3D} and used the equivalent continuous medium seepage model. The above research fully verified the reliability of FLAC^{3D} software to simulate the unsaturated fluid-structure coupling, but the water absorption of expansive soil will produce swelling strain, which is a typical stress-swelling-seepage multi-field coupling problem. So how to introduce swelling strain into the unsaturated fluid-solid coupling model has become a major difficulty in the coupling analysis of expansive soils. So how to introduce swelling strain into the unsaturated fluid-solid coupling model has become a major difficulty in the coupling analysis of expansive soils.

Based on the finite difference seepage theory, using the FISH language programming built in the FLAC^{3D} software, the expansion strain is introduced into the unsaturated fluid-solid-coupling model, and the unsaturated expansive soil expansion-seepage-stress multi-field coupling analysis method is constructed. By establishing two numerical models of a crack-free homogeneous expansive soil slope just after excavation and a cracked expansive soil slope under repeated drying and wetting cycles. The unsaturated infiltration process of the expansive soil slope under rainfall conditions is reproduced, discussed the change law of the temporal and spatial distribution of moisture migration in unsaturated expansive soil, and the influence of swelling deformation on the distribution of wetting front and transient area ratio.

2. Multi-field Coupling Analysis Method of Unsaturated Expansive soil

2.1 Establishment of Numerical Model

The quasi-static Biot theory is a method of calculating unsaturated seepage by the finite difference software FLAC^{3D}. It connects the saturation, pore pressure and volume strain of the porous media structure to establish a relationship.Assuming that the influence of gas phase is not considered in the unsaturated seepage flow, the expression of the fluid continuity equation is:

$$\frac{1}{s}\frac{\partial\zeta}{\partial t}=\frac{1}{M}\frac{\partial u_w}{\partial t}+\frac{n}{s}\frac{\partial s}{\partial t}+\alpha\frac{\partial\varepsilon_v}{\partial t} \tag{1}$$

Where, s is the saturation, u_w is the pore water pressure; ε_v is the volumetric strain; M is the Biot modulus; α is the Biot coefficient; ζ is the fluid volume change during the water migration of the porous medium; n is the porosity; t is the migration time.

The calculation process of unsaturated seepage follows Darcy's law:

$$q_i=-k_{il}k(s)\left[u_w-\rho_f x_j g_j\right]_{,j} \tag{2}$$

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Where, $k(s)$ is the relative permeability coefficient of the porous medium; ρ_f is the fluid density; g_j is the acceleration of gravity; k_{il} is the saturation permeability coefficient tensor; k_{il} is the saturated permeability coefficient tensor.

Under the assumption of small strain, for a fluid with low compression, the expression of the fluid mass balance equation is:

$$\frac{\partial \zeta}{\partial t} = -\frac{\partial q_i}{\partial x_i} + q_v \tag{3}$$

Where, q_v is the strength of the fluid source. The law of saturation and permeability coefficient changing with matrix suction is an indispensable hydraulic parameter for unsaturated seepage calculation. SWCC adopts Fredlund & Xing model [12] to fit.

$$\begin{cases} s = C(\psi)\dfrac{1}{\{\ln[\mathrm{e} + (\psi / a)^n]\}^m} \\ C(\psi) = 1 - \dfrac{\ln(1 + \psi / \psi_r)}{\ln(1 + 1000000 / \psi_r)} \end{cases} \tag{4}$$

Where, s is the saturation; a is the air intake value in kPa; e is a natural number; ψ is the matrix suction; m controls the parameter of residual water content; n controls the slope of the soil-water characteristic curve. The permeability coefficient of the unsaturated zone changes with the saturation, and is defined as the product of the relative permeability coefficient and the saturated permeability coefficient:

$$k = k_s k(s) = k_s s^2 (3 - 2s) \tag{5}$$

Bishop proposed the effective stress principle based on the condition that the unsaturated soil needs to consider the influence of matrix suction. In order to simplify the mechanical calculation, the Bishop parameter is assumed to be saturation, and the effective stress relation is:

$$\sigma'_{ij} = \sigma_{ij} + s u_w \tag{6}$$

In the formula σ_{ij} and σ'_{ij} is the total stress and effective stress.

2.2 Introduction of expansion strain

The stress-strain relationship and the moisture content-strain relationship of expansive soil obey Hooke's law in the elastic stage, and the expansion strain is added to the total strain in the form of additional strain. When the expansion of expansive soil is constrained by water absorption, the expansion strain in the elastic phase is limited, and the total strain tensor is:

$$\varepsilon_{ij} = \varepsilon_{ij}^{\sigma} + \varepsilon_{ij}^{w} \tag{7}$$

With the introduction of expansibility, the continuity equation of seepage flow corresponding to multi-field coupling will also change, and its expression is:

$$\frac{1}{s}\frac{\partial \zeta}{\partial t} = \frac{1}{M}\frac{\partial u_w}{\partial t} + \frac{n}{s}\frac{\partial s}{\partial t} + \alpha\frac{\partial \varepsilon_{ij}^{\sigma}}{\partial t} + \alpha\frac{\partial \varepsilon_{ij}^{w}}{\partial t} \tag{8}$$

Assuming that the expansion strain in the three directions of the expansive soil is the same along the principal strain direction, and no shear strain is generated, the expansion strain component is:

$$\begin{cases} \varepsilon_x = \varepsilon_y = \varepsilon_z = \varepsilon_{ij}^{w} \\ \varepsilon_{yz} = \varepsilon_{xz} = \varepsilon_{xy} = 0 \end{cases} \tag{9}$$

Expansive soil receives internal and external constraints in the process of water absorption and loss, and the expansion strain caused by the change of water content cannot occur freely. According to the theory of elastic increment, the expansion strain is taken as the additional strain of the elastic body into the strain component and rewritten as the total stress expression:

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$$\begin{cases} \sigma_x = \dfrac{E(1-\nu)}{(1+\nu)(1-2\nu)}\varepsilon_x + \dfrac{E\nu}{(1+\nu)(1-2\nu)}\left(\varepsilon_y+\varepsilon_z\right)+\dfrac{E}{1-2\nu}\varepsilon_{ij}^{w} \\ \sigma_y = \dfrac{E(1-\nu)}{(1+\nu)(1-2\nu)}\varepsilon_y + \dfrac{E\nu}{(1+\nu)(1-2\nu)}\left(\varepsilon_x+\varepsilon_z\right)+\dfrac{E}{1-2\nu}\varepsilon_{ij}^{w} \\ \sigma_z = \dfrac{E(1-\nu)}{(1+\nu)(1-2\nu)}\varepsilon_z + \dfrac{E\nu}{(1+\nu)(1-2\nu)}\left(\varepsilon_x+\varepsilon_y\right)+\dfrac{E}{1-2\nu}\varepsilon_{ij}^{w} \end{cases} \tag{10}$$

3. Numerical model and modeling analysis

In order to analyze the change process of unsaturated seepage of expansive soil slope under rainfall, a three-dimensional slope grid numerical model is established as shown in Figure 1. The model adopts the equivalent permeability continuum model to simulate the engineering characteristics of the upper fractured expansive soil. The grid units are divided into hexahedral grids. The lengths in the three directions of X, Y, Z are 36m, 10m and 17m respectively, the slope height is 10m, and the slope ratio is 1:2The slope material parameters are shown in Table 1.

Table 1. Calculation parameters

Material parameter/unit	Fractured soil		Undisturbed soil	
	Natura state	Saturation state	Natural state	Saturation state
Solid phase expansion	$\varepsilon_w = 0.005 w_0^{-1.894}\ln(\frac{e(w-w_0)+(0.31-w)}{0.31-w_0})$			
Solid phase elastic modulus/kPa	$E(P,w)=(0.45w+0.066)P-523.93w+152.61$			
Solid Poisson's ratio	$v(P,w)=0.0002P+0.4-\frac{(0.2-0.4)}{1+\exp\left(\frac{w-0.198}{0.03}\right)}$			
cohesion/ kPa	$c=20.8e^{-1.58w_0}$		$c=96.2e^{-2.21w_0}$	
internal friction angle/°	$\varphi=-10.2w_0+17.1$		$\varphi=-13.5w_0+25.3$	
Solid phase density/ kg·m^{-3}	1800	2000	1980	2130
Initial porosity	0.43		0.39	
permeability coefficient/ m·s	5.5×10^{-7}		1.6×10^{-8}	
Fredlund & Xing model parameters	a=10, n=2.3, m=0.75		*a*=23, *n*=2, *m*=0.7	
Liquid bulk modulus/kPa	2.0×10^{6}			
Acceleration of gravity/m·s^{-2}	9.806			

The hydraulic, swelling, deformation and strength parameters of expansive soil materials adopt experimental fitting results. The fractured soil adopts the SWCC curve fitted by the Fredlund & Xing model under the 25kPa stress loading path of the upper soil. The undisturbed soil adopts the SWCC curve fitted by the Fredlund & Xing model under the 100kPa stress loading path of the underlying soil, Set the initial water level at the foot of the slope (z=7m), the top of the model is set as the boundary of rainfall infiltration and seepage, and the base and surroundings of the model are set as impervious boundaries. According to the local meteorological data of Ningming area, the planned rainfall intensity is 9.62×10^{-7} m/s, the rainfall lasts for 3 days, and the rain stops lasts for 4 days. Figure 2 shows the initial pore pressure field generated by the FISH function according to the assumption that the matrix suction is linearly distributed along the height.

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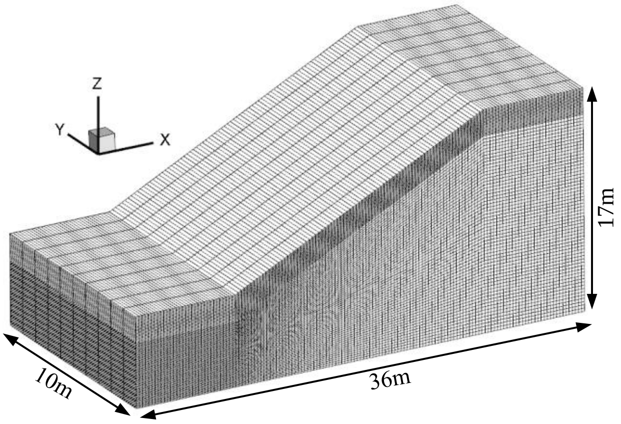

Figure 1. Mesh model

The expansive soil slope is distributed with fissure soil within the depth of 1-2m from the slope surface, and the original soil is below 2m. The specific parameter values are shown in Table 5.1. The initial humidity fields of the two models are generated according to the SWCC curve as shown in Figure 3.

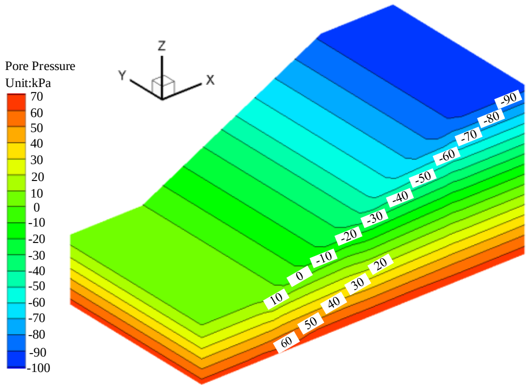

Figure 2. Initial pore pressure field

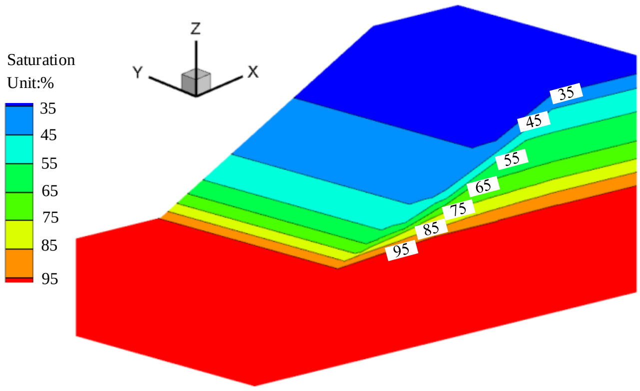

Figure 3. Initial humidity field

4. Calculation results and analysis

4.1 Variation law of the moisture field of unsaturated expansive soil

Figure 4 shows the evolution law of the unsaturated humidity field during the water migration process of the fractured expansive soil slope, combined with the analysis of the change law of the wet front in the middle of the slope with the rainfall duration in Figure 5. It can be seen that the change of the slope humidity field is inseparable from the rainfall infiltration. With the passage of rainfall, the range of the suspended transient saturation zone gradually increases, and the groundwater level also rises. The rise of the water level makes the suction of the matrix within this range completely lost, and the weight of the soil increases. When the rainfall is 3 days, the rainfall infiltration depth is close to the buried depth of 1.5~1.75m. Two obvious saturation change zones are formed in the boundary zone of saturated-unsaturated zone (buried depth 1.5~1.75m) and the boundary zone between cracked soil and undisturbed soil (buried depth 2m). During the intermittent period of rainfall, the wet front will further expand downward, and its rainfall infiltration depth will gradually reach the undisturbed soil layer (buried depth below 2m). At this time, the moisture near the slope surface is homogenized due to the infiltration and infiltration into the slope, but the speed of homogenization is slow. This shows that the humidity field of expansive soil slopes has a time lag type during the intermittent period of rainfall, and the water will stay in the shallow range of the slope.

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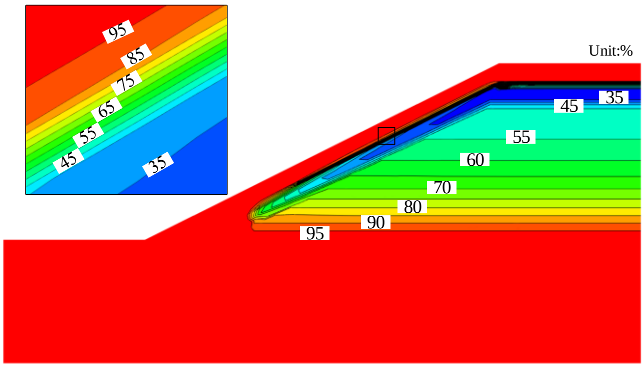
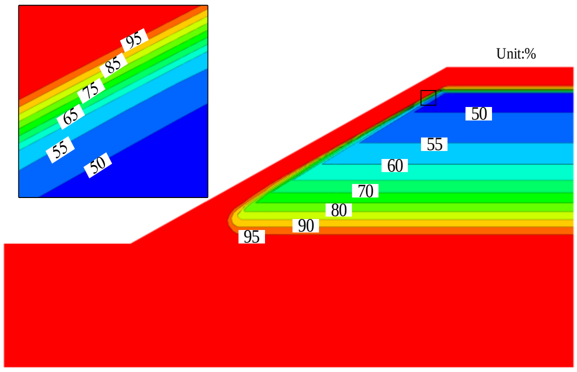


(a). Rain 3d



(b). Stop rain 4d

Figure 4. Changes in the humidity field with fissures

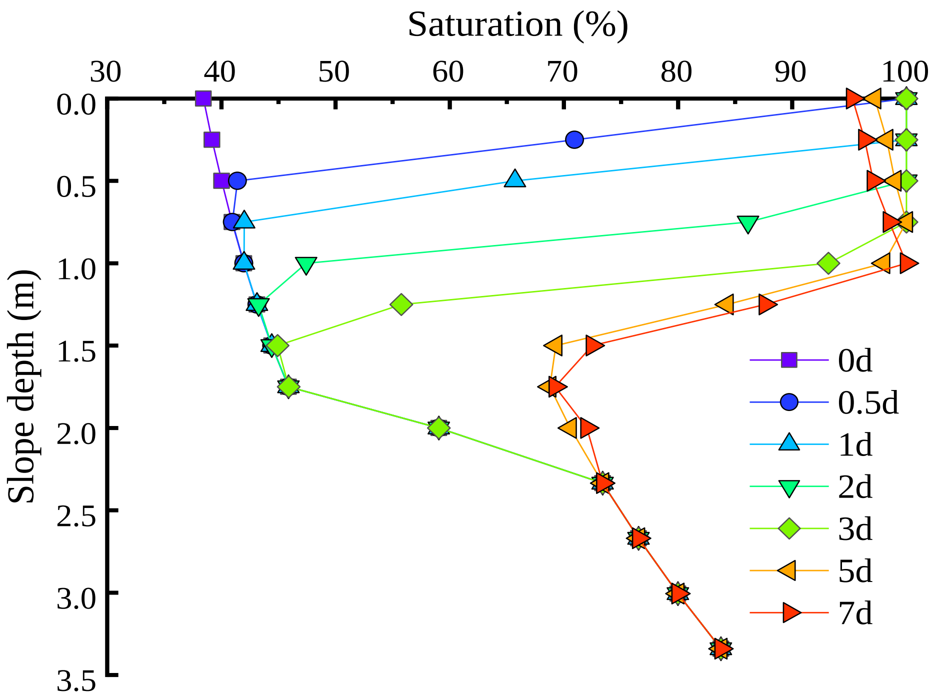


Figure 5. Variation law of wet front with rainfall duration (central part of slope)

4.2 Variation law of pore water pressure of unsaturated expansive soil

Figure 6 shows the cloud diagram of the change of the slope pore water pressure field, it is not difficult to see that as the rainfall duration increases, the negative pore water pressure on the slope gradually increases and turns to a positive value, forming a transient water pressure. During this period, the water near the top of the slope collects to the toe of the slope along the wet surface area, resulting in the toe of the slope being significantly more affected by rain than the top of the slope. The closer to the toe of the slope, the greater the area of transient water pressure, a large-scale saturation zone is formed at the toe of the slope, and the groundwater level is raised. As rainfall mainly affects the pore water pressure of shallow slopes, there is no significant change in pore water pressure of deep slopes. When the rainfall ends for a period of time, the lower pore water pressure increases as the wet front continues to expand inward, the hydraulic gradient slows down, and the area affected by rainfall infiltration expands. However, due to the loss of rainwater replenishment during the rain stop, the water in the slope is discharged outwards, the pore pressure of the slope surface is slightly reduced with the wetting front, and the zero pore pressure surface near the slope toe drops.

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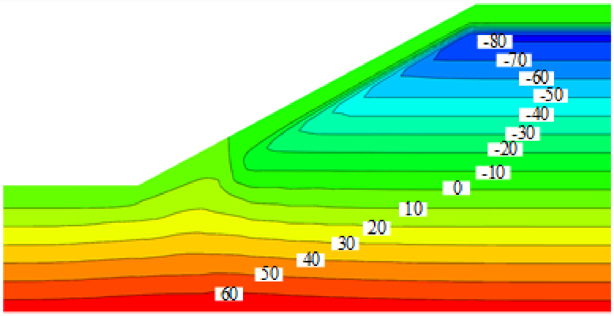
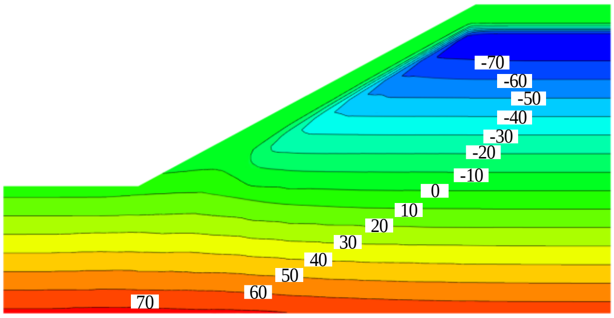


(a). Rain 3d



(b). Stop rain 4d

Figure 6. Cloud diagram of changes in pore water pressure field (Unit:kPa)

Figure 7 depicts the time-history variation of pore water pressure at six characteristic points with a buried depth of 1m. It can be seen that the time-history changes of pore water pressure at the characteristic points with a depth of 1m at different positions on the slope have experienced three stages: a slow increase, a rapid rise, and a plateau, that is the trend of "slow-increase-slow". The closer to the characteristic point of the slope toe, the greater the influence of rainwater infiltration and the collection water flowing from the top of the slope to the slope toe, and the earlier the pore water pressure changes. The wet front will be the first to reach a buried depth of 1m and enter a period of rapid ascent ahead of schedule. However, because the initial pore water pressure at the toe of the slope is smaller than the initial pore water pressure at the top of the slope, the rise of the slope toe is small, and finally the pore water pressure at the toe of the slope first experiences a plateau. In the intermittent period of rainfall, the pore water pressure is basically in a stable period, reaching a saturated state, and the pore water pressure at the characteristic point from the foot of the slope to the slope top is distributed from large to small.

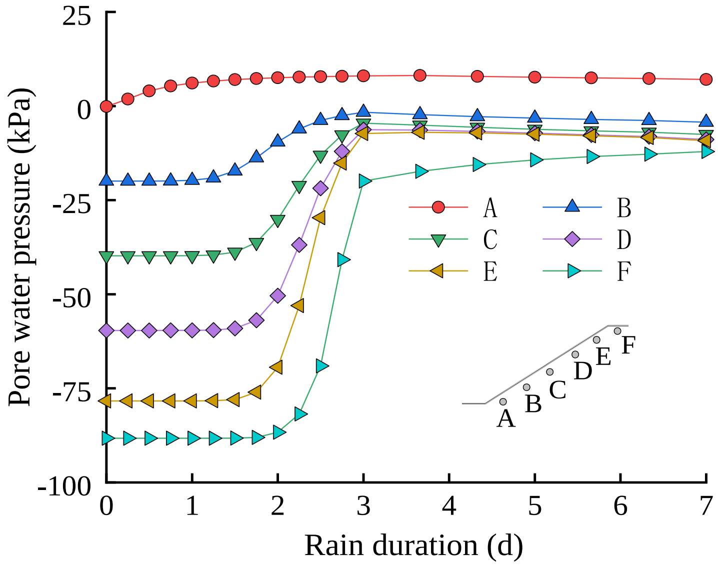


Figure 7. Time history change law of pore water pressure (buried depth 1m)

4.3 Influence of swelling deformation on unsaturated seepage field

In order to illustrate the influence of expansive soil on the slope unsaturated seepage in the process of water migration, the distribution of the influence of expansion deformation and disregarding expansion deformation on the wet front in the middle of the slope (x=18m) is shown in Figure 8. It can be seen that during the rainfall process, the wet front migrates into the slope in a saturated state, the range of the transient saturated zone increases downwards in a hanging shape, and the rainfall

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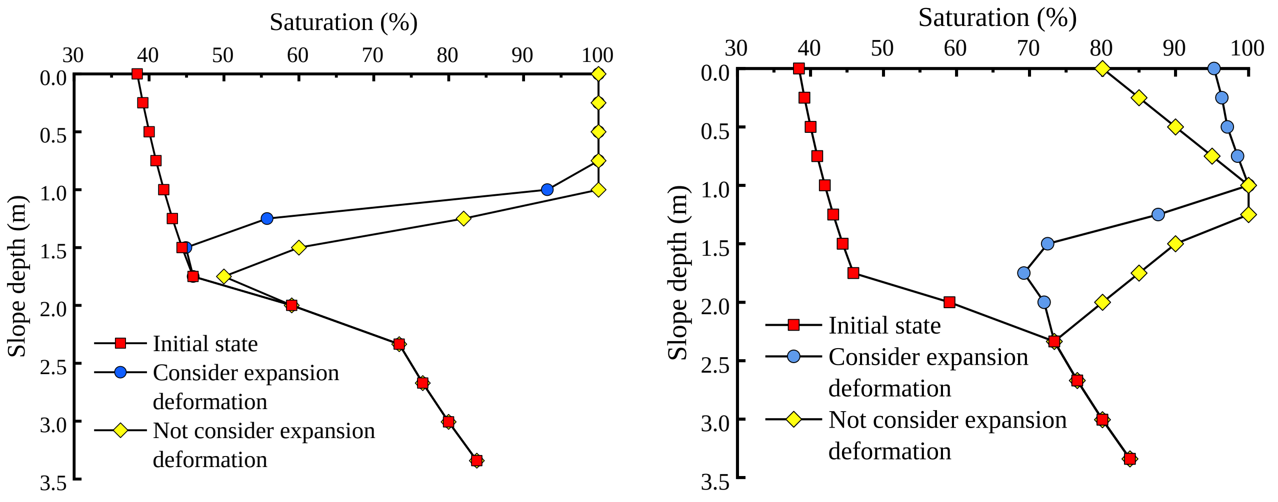
infiltration depth gradually expands. When the rain is over (rain 3d), the depth of saturated wet front with and without expansion deformation is 0.75m and 1m, respectively, and the depth of rainfall infiltration is between 1.5~1.75m and 1.75~2m, respectively. This shows that the expansion depth of the saturated wet front, the range of the transient saturation zone, and the depth of rainfall infiltration considering the expansion and deformation during the rainfall period is less than that of the expansion and deformation. The reasons for the above phenomenon are: First Rainfall infiltration causes uneven temporal and spatial distribution of the unsaturated seepage field of expansive soil slopes, and it is accompanied by expansion and deformation during the rainfall process. Secondly, the internal soil of the slope is compacted due to water swelling, and the volume of soil particles increases, resulting in internal expansion and pressure. Finally, the internal bulging pressure narrows the pore channels for rainwater infiltration, and the permeability of the soil becomes worse, which inhibits the spreading speed of the wet front into the slope and the process of water diffusion.

It can also be seen from Figure 8. that during the intermittent period of rainfall, the upper wet front of the expansive soil slope is gradually homogenized due to the infiltration of the slope. At the same time, the lower wet front continues to expand into the slope due to gravity, and the depth of rainfall infiltration continues to expand, the range of the transient saturation zone shows a typical time lag after the rain. When the rainfall ends for 4 days, the rate at which the upper edge of the wet front is homogenized and the rate at which the lower edge expands when expansion and deformation are considered is slower than that without expansion and deformation. The rainfall infiltration depth of both is 2.25m. At this time, the change range of the humidity field when expansion deformation is considered is lower than when expansion strain is not considered. The reasons for analyzing the above phenomenon are: First of all, during the period of no rain, the speed and path of water diffusion inside the slope are controlled by the size of expansion and deformation. Secondly, when considering expansion and deformation, since the wetting front at this stage is greater than the initial wetting front, the process of infiltration and infiltration of the surface slope continues to be inhibited by expansion and deformation. Finally, because the infiltration is inhibited, the speed of water migration slows down, which makes it difficult for rainwater to seep and seep. After rain, water is easy to accumulate in the pores of the shallow soil on the slope.



(a). Rain 3d (b).Stop rain 4d

Figure 8. Distribution of the influence of swelling deformation on the wetting front (central part of the slope)

5. Conclusion

(1) The impact of rainfall infiltration on the slope seepage field is mainly concentrated in the shallow layer. The increase in rainfall duration accelerates the process of the expansion of the wet front.

During the intermittent period of rainfall, the water migration of the topsoil is limited, resulting in the insignificant changes in the expansion of the lower wet front and the homogenization of the upper wet front. In this period, the slope with cracked soil will form two obvious saturation change zones at the boundary of the soil layer.

(2) As the rainfall continues, the pore water pressure of the slope gradually increases to form a transient water pressure, and the pore water pressure shows gradual-increasing-slowing trend. After the rain has stopped for a period of time, as the wet front continues to expand inward, the lower pore water pressure will increase and the infiltration affected area will expand.

(3) After considering the expansion and deformation, the transient saturated area, the expansion of rainfall infiltration depth and the rate of change of transient area ratio. During the intermittent period of rainfall, expansive soil slopes are gradually homogenized due to the infiltration of the upper wet front.

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