Research Article

Influence of Layer Transition Zone on Rainfall-Induced Instability of Multilayered Slope

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Although numerous studies have been paid much attention to rainfall-induced instability of multilayered slopes, the interface between layers is generally considered to be "zero thickness", and the layer transition zone between layers is neglected. In this study, the influence of the layer transition zone on the rainfall-induced instability of multilayered slope was investigated. A model was developed to simulate the rainfall infiltration process, the distribution of pore water pressure, and the stability of multilayered slope by coupling the unsaturated seepage model and the slope stability analysis method. Based on the analysis of the multilayered slopes with the different thickness ratios of the layer transition zone, a method for determining the critical thickness of the layer transition zone was proposed. The results showed that the layer transition zone had a significant influence on the stability of multilayered slope. It was found that the presence of the layer transition zone in the multilayered slope reduced the hydraulic conductivity of the slope and increased the rate of formation of transient saturated zone, which contributed to excess pore water pressure at the toe of the slope. The analysis of the local factor of safety (LFS) showed that when the thickness ratios of the layer transition zone were between 2.5% and 5%, the corresponding hydraulic conductivity of the slope decreased by 1%-2.5% and the maximum failure area of the slope during the rainfall was 25% of the slope. Our study highlighted the importance of the layer transition zone for the rainfall-induced instability of the multilayered slope.

1. Introduction

Landslides are serious geologic hazards in mountainous regions and are usually triggered by the rainfall events. Slope stability is an important part of geotechnical and hydraulic engineering research [1, 2]. Multilayered slopes are ubiquitous in nature due to the geological deposition process. The different soil layers often have great differences in their geotechnical properties. Under rainfall infiltration, the stability of these multilayered slopes is closely related to the inherent spatial variability of geotechnical properties, especially the permeability of the soil layer.

In recent years, numerous studies have addressed the stability of multilayered slopes under rainfall infiltration [3–5]. Using the upper bound limit analysis, a method for calculating the stability numbers for multilayered slopes was proposed [6], where it was assumed that the failure surface is a combination of different logarithmic spiral arcs with a common focus. This method ensures the kinematic admissibility of the collapse mechanism with respect to the rigid rotation of the bounded soil mass about the focus of the logarithmic spiral. Zheng et al. [7] developed general three-dimensional kinematically rotational failure mechanisms for two-layer soil slopes, which not only considered the back slope angle but also included the mechanisms of face failure, toe failure, and base failure. From the perspective of rainfall infiltration process, the infiltration model was proposed to analyze the influences of rainfall infiltration on the water content, pore water pressure, and slope stability [8]. In addition, previous studies [9, 10] modified the traditional infiltration model and numerical method for slope stability to analyze the temporal and spatial evolution of soil water content and pore water pressure during the rainfall infiltration. Although the seepage characteristics and instability...
mechanism of multilayered soil slopes during rainfall infiltration were analyzed by different methods, the presence of the layer transition zone between layers was neglected.

Layers exhibit different pore space structures and hydraulic properties due to grain size contrast. In the zone near the layer interface, the grain size changes from one side to the other [11, 12]. The transition of grain size between layers is due to the complex geological process [13–16]. The deposited grains in different geological periods may mix, resulting in a grain-sized transition zone with a small thickness. However, the grain-sized transition zone in multilayered soil slope is generally neglected and roughly assumed to be a “zero thickness” plane due to its small thickness. This rough assumption may be reasonable for estimating the hydraulic properties of the multilayered soil slope at field or laboratory scale [17]. However, it is inappropriate for studying seepage characteristics and instability mechanism of the multilayered soil slope which is largely controlled by flow behavior at the pore scale.

Moreover, rainfall infiltrates the soils along a gravitational gradient and forms a perched water table in the soil [18]. The heterogeneity of the layer in the slope has a significant influence on the distribution of infiltrated water. In highly heterogeneous slopes, the pore space structure in the slope is complex and has different types of pore space, such as macropores, fractures, cracks, or large pores. These pore spaces in turn have a significant influence on the seepage characteristics. For example, water preferentially flows through the local high permeability zones, which results in the high pore water pressure [19]. Although the influence of heterogeneity of geological formations on seepage characteristics has been confirmed and studied in various fields, such as water resources, oil production, and groundwater remediation [20–22], the influence of the layer transition zone as a special heterogeneity of slope has not been incorporated into slope stability analysis.

Slope stability analysis is usually performed using limit equilibrium methods because they have been proven to be effective and reliable [23–26]. In these methods, the location of the potential failure surface is approximated or predetermined. All two-dimensional limit equilibrium methods consist of discretizing the mass of a potential failure slope into smaller vertical slices. All limit equilibrium methods assume that each individual slice is treated as a unique sliding block and shear strength is mobilized with the same ratio of shear stress to shear strength for all slices. In order to quantify the slip surface and factor of safety, many advanced geotechnical engineering software and numerical models (e.g., FLAC®, PLAXIS, and COMSOL Multiphysics) have been widely used. These models are particularly suitable for the quantitative analysis of the slope stability under the influence of transient hydrological conditions. Zhou et al. [27] compared the limit equilibrium method and the finite element shear strength reduction method. They used COMSOL Multiphysics software to model the infiltration of reservoir water and rainfall into the sliding mass. Shao et al. [28] coupled subsurface flow model and plane strain linear elasticity model to quantify the influence of preferential flow on slope stability based on COMSOL Multiphysics software.

The main objective of this study is to investigate the influence of the layer transition zone on the rainfall-induced instability of the multilayered soil slope. For this, a double-layer soil slope with a layer transition zone was constructed based on the previous study [28]. The unsaturated seepage model was sequentially coupled with a soil mechanics model based on COMSOL 5.6 Multiphysics (COMSOL Inc., Burlington, MA, USA). The slope stability was analyzed by a stress field-based local factor of safety (LFS). The rainfall infiltration process, pore water pressure distribution, and LFS of multilayered soil slope with and without layer transition zone were compared and analyzed. In addition, a critical thickness of the layer transition zone was introduced and determined.

2. Methodology

2.1. Unsaturated Seepage Model. In this study, Richards’ equation was used to describe the unsaturated flow in a homogeneous soil. The corresponding equation is given as follows:

$$[C + S_{\alpha}] \frac{\partial h}{\partial t} = \nabla [K(h) \nabla h]$$

where $C$ is the differential water capacity, $S_{\alpha}$ is the effective saturation, $h$ is the specific storage, and $K(h)$ is the isotropic hydraulic conductivity.

To quantify the hydraulic properties of the soil layer, the classical Brooks-Corey model was used, which is given as follows:

$$S_{\alpha} = \frac{\theta - \theta_s}{\theta_r - \theta_s} = \begin{cases} \left(\frac{\alpha_{BC} h}{h_{BC}}\right)^{\alpha_{BC}}, & \alpha_{BC} h < -1, \\
1, & \alpha_{BC} h \geq -1,
\end{cases}$$

$$C = \begin{cases} \alpha_{BC} h_{BC} (\theta - \theta_r) \left(\frac{\alpha_{BC} h}{h_{BC}}\right)^{-\alpha_{BC}}, & \alpha_{BC} h < -1, \\
0, & \alpha_{BC} h \geq -1,
\end{cases}$$

where $\theta$ is the water content, the subscripts $s$ and $r$ denote the saturation and residual saturation, and $\alpha_{BC}$ and $h_{BC}$ are the fitting parameters. The hydraulic conductivity can be determined by the following:

$$K = K_s S_{\alpha}^{2l_{BC} + h_{BC} + 2}.$$
stress field of the slope was determined by the plane strain linear elasticity model [30], which is governed by a momentum balance equation:

\[ \nabla(\sigma) + \gamma(\theta) b = 0, \]  

(4)

where \( \sigma \) is a stress tensor with three independent stress variables in two-dimensional space, \( \gamma \) is the bulk unit weight of the slope material, and \( b \) is the unit vector of body forces with two components. Here, Bishop’s effective stress criterion is considered. This means that all the pores in the slope are connected to the atmosphere and the air pressure in the pore is equal to the atmospheric pressure. Therefore, Bishop’s effective stress criterion is defined as follows:

\[ \sigma' = \sigma - \chi p_W, \]  

(5)

where \( \sigma' \) is the effective stress, \( p_W \) is the pore water pressure, and \( \chi \) is the matrix suction coefficient which can be estimated by the effective saturation.

The local factor of safety (LFS) method [29] defines the ratio of the ultimate Coulomb stress to the actual Coulomb stress at each point in the stress field as the LFS. Thus, once the stress field of the slope was determined, the scalar field of local factor of safety (LFS) can be obtained as follows:

\[ F_{\text{LFS}} = \frac{\tau^*}{\tau}, \]  

(6)

where \( \tau^* \) is the limit Coulomb stress and \( \tau \) is the actual shear stress. According to Mohr-Coulomb failure criterion, Equation (6) can be redefined in terms of LFS:

\[ F_{\text{LFS}} = \frac{2 \cos \varphi'}{\sigma_1' - \sigma_3'} \left[ e' + \frac{\sigma_1' + \sigma_3'}{2} \tan \varphi' \right], \]  

(7)

where \( e' \) is the effective cohesion, \( \varphi' \) is the friction angle, and \( \sigma_1' \) and \( \sigma_3' \) are the spatially varying first and third principal effective stresses for the unsaturated soil.

### 3. Verification of Model and Setup of the Numerical Experiments

#### 3.1. Verification of Model

In order to verify the established numerical model, a previous slope geometry and the corresponding parameters [28] were used. The corresponding parameters are listed in Table 1.

The established slope is 6 m high and 15 m long, which consists of two oil layers. The upper soil layer is sandy loam with a thickness of 2 m and the lower part is clay. In order to avoid the influence of specified boundary conditions, the slope is extended along the boundaries as shown in Figure 1.

For the seepage field, the upper surface of the slope was set as the atmospheric boundary and rainfall boundary. The left and bottom sides were set as impermeable boundaries. The upper sand on the right side was set as the potential seepage surface boundary, and the lower clay on the right side was set as the pressure boundary to simulate groundwater table. A mixed boundary condition [31] was implemented to simulate the rainfall infiltration process. The real-time dynamic transformation of the mixed boundary condition was implemented by incorporating a step function and coupling with the corresponding boundary conditions. When the rainfall intensity was less than the infiltration capacity of the soil surface in the slope, the mixed boundary condition was transformed into constant flow boundary, while the rainfall intensity was greater than the infiltration capacity of the soil surface in the slope; the constant head boundary condition was implemented for the mixed boundary condition. It should be mentioned that the infiltration capacity of the soil depends on the types of the soil. The mixed boundary assumes that the rainfall boundary is the constant head boundary and the ponding depth is 0.5 mm [32].

For the stress field, the slope surface was set as a free surface and all other boundaries of the slope were set as the role support boundary. This means that the boundary condition in the stress field only constrains the normal displacement.

### Table 1: The parameters in the model.

| Symbol | Unit | Upper layer (sandy loam) | Lower layer (clay) |
|--------|------|--------------------------|--------------------|
| \( \rho_i \) | (-) | 0.412 | 0.385 |
| \( \rho_t \) | (-) | 0.041 | 0.09 |
| \( K_s \) | (cm/h) | 2.59 | 0.06 |
| \( \sigma_{BC} \) | (m\(^{-2}\)) | 0.068 | 0.027 |
| \( n_{BC} \) | (-) | 0.322 | 0.131 |
| \( l_{BC} \) | (-) | 1 | 1 |
| \( \gamma_{dry} \) | (kN/m\(^3\)) | 15.5 | 15.5 |
| \( E \) | (MPa) | 10 | 10 |
| \( \mu \) | (-) | 0.35 | 0.35 |
| \( \sigma' \) | (-) | 35 | 35 |
| \( \varphi' \) | (-) | 3 | 6 |

![Figure 1: Computational domain of the multilayered slope and the boundary conditions.](image)
To obtain the initial condition of the steady pore water pressure distribution in the slope, a daily rainfall of 1.64 mm/d was applied for 10 years. Then, a rainfall event with a high-intensity rainfall of 20 mm/h for 15 hours was simulated. From Figure 2, it can be seen that the results of water content distribution at both \( t = 0 \) and \( t = 10 \) hours are consistent with the previous study [28], indicating that the established numerical model in this study is valid and accurate.

### 3.2. Setup of the Numerical Experiments

In order to quantitatively evaluate the influence of layer transition zone on the seepage characteristics and stability of multilayered soil slope under rainfall infiltration, the rainfall infiltration process and the distribution of pore water pressure and LFS in multilayered soil slope were investigated by numerical modelling. Based on the above verified model, one multilayered soil slope without the layer transition zone and eight multilayered soil slopes with the different thickness ratios of layer transition zone to the upper sand layer were constructed. The thickness ratios for the layer transition zone were 2.5%, 5%, 10%, 15%, 20%, 25%, 40%, and 50%, respectively. As shown in Figure 1, the boundary conditions are consistent with the verified model. Figure 3 shows the multilayered soil slope with the layer transition zone.

Since, in this study, we mainly focused on the influence of layer transition zone on rainfall-induced instability of multilayered soil slope, it is assumed that the saturated hydraulic conductivity changes linearly along the normal direction of the interface between layers. Thus, if the normal distance from any point \((x, y)\) in the layer transition zone to the interface under the sand layer is \(d\), the saturated hydraulic conductivity of that point is given by the following:

\[
K = K_1 - \frac{K_1 - K_2}{D} d, \tag{8}
\]

where \(K_1\) and \(K_2\) are the saturated hydraulic conductivities for the upper sandy layer and the lower clay layer, respectively. More specifically, the saturated hydraulic conductivity of the layer transition zone for the constructed multilayered soil slope is determined by the following:

\[
K = \begin{cases} 
K_1 - \frac{(K_1 - K_2)}{a} (23 + a - y), & 0 \leq x \leq 17, \\
K_1 - \frac{K_1 - K_2}{5a} |2x + 5y - 149 - 5a|, & 17 < x < 32, \\
K_1 - \frac{(K_1 - K_2)}{a} (17 + a - y), & 32 \leq x \leq 42,
\end{cases} \tag{9}
\]

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**Figure 2**: Verification of model by the previous results in the reference [28].

**Figure 3**: Schematic diagram of the multilayered soil slope with the layer transition zone.

**Figure 4**: Coordinate system of the multilayered soil slope with layer transition zone.
where \( a \) represents the thickness of the layer transition zone as shown in Figure 4.

4. Results and Discussion

4.1. Influence of Layer Transition Zone on Rainfall Infiltration Process. Since the initial distribution of water content in the multilayered slope has a significant influence on the evolution of water content, in this study, eight multilayered slopes with different thickness ratios of the layer transition zone and one multilayered slope without the layer transition zone were established under a daily rainfall of 1.64 mm/d for 10 years to obtain the initial distributions of water pressure and water content. To illustrate the influence of the layer transition zone, only the multilayered slope with the thickness ratio of 25% is presented in the following sections.

Figure 5 shows the evolution of water content in the multilayered slopes with and without the layer transition zone. From Figure 5, it can be seen that at \( t = 0 \) h, there is no significant difference in the spatial distribution of the initial volumetric water content in the two slope models and the initial water table is near 18 m, which is due to the linear change in the permeability of the layer transition zone. This result also shows that the layer transition zone has no significant influence on the spatial distribution of the initial water content in the slope. At \( t = 3 \) h, as the rainfall infiltration proceeded, the wetting front in the multilayered slope with the layer transition zone reaches the groundwater table faster than the wetting front in the multilayered slope without the layer transition zone. The infiltrated water forms the transient saturated zone at the toe of both multilayered slope without and with the layer transition zone. Due to the linear change in the permeability of the layer transition zone, the infiltrated water in the multilayered slope with the layer transition zone is difficult to be discharged and leads to the accumulation of the infiltrated water at the toe of the slope. This leads to a rapid increase in water content at the toe of the slope toe. This also indicates that the layer transition zone accelerates the formation and development of the transient saturation zone. Furthermore, after \( t = 9 \) h, there is little difference from the transient saturated zone in both the multilayered slopes with and without the layer transition zone. This indicates that the influence of the layer transition zone on transient saturation zone is mainly reflected in the early stage of rainfall, while it is weak in the late stage of rainfall.
Figure 6 shows the spatiotemporal distribution of water content in lines 1-1 and 1-1’. Note that since the soils in the entire line of both the multilayered slope with and without layer transition zone are saturated after $t=7$ h, the distribution of water content after $t=7$ h is not present in Figure 6. From Figure 6, it can be seen that the soils in line 1-1 are saturated after $t=5$ h, while the soils in line 1-1’ are saturated after $t=7$ h. This indicates that on the one hand, the water content in the multilayered slope with the layer transition zone is much higher than without the layer transition zone at the same time, and on the other hand, the layer transition zone has a significant influence on the spatiotemporal distribution of the water content. This is because that the presence of the layer transition zone in the multilayered slope decreases the local hydraulic conductivity, which causes the saturation zone in the multilayered slope to form faster with the layer transition zone than without the layer transition zone. Therefore, under the same rainfall infiltration process, the presence of the layer transition zone in the multilayered could enhance the accumulation of the infiltrated water and accelerate the formation of the transient saturation zone.

4.2. Influence of Layer Transition Zone on Distribution of Pore Water Pressure. Figure 7 shows spatiotemporal evolution of the pore water pressure in the multilayered slopes with and without the layer transition zone. As shown in Figure 7, it can be seen that at $t=0$ h, the initial distribution of pore water pressure in the multilayered slope with and without the layer transition zone is the same. However, it is found that the pore water pressure is larger in the layer transition zone than in the same zone without the layer transition zone at the toe of the slope. This is because that the low permeability of the layer transition zone leads to the accumulation of the infiltrated water.

From $t=0$ h to $t=9$ h, the pore water pressure at the surface of the slope increases and the wetting front advances further into the interior of the slope, which is accompanied by an increase in the water content of the slope. The increasing water content gradually advances, indicating that the influence of rainfall infiltration on pore water pressure also gradually increases. From Figure 7, it can be found that not only the pore water pressure at the toe of the slope but also the influence of rainfall infiltration on the pore water pressure is greater for the multilayered slope with the layer transition zone than without the layer transition zone. This is because that compared with the multilayered slope without the layer transition zone, the transient saturation zone forms faster and the water content increases rapidly. This result indicates that under the rainfall infiltration, the...
presence of layer transition zone can accelerate the increase of pore water pressure of the slope, especially at the toe of the slope.

From $t = 9h$ to $t = 15h$, the pore water pressure increases as the rainfall infiltrated in both the multilayered slopes with and without the layer transition zone. However, the pore water pressure increases faster at the toe of the multilayered slope with the layer transition zone than without the layer transition zone. Although the seepage field in both the multilayered slopes with and without the layer transition zone is steady after $t = 9h$, the increased pore water pressure cannot be effectively dissipated due to the rapid accumulation of pore water during the early rainfall. Therefore, it can be concluded that the influence of the layer transition zone on the pore water pressure exists throughout the whole process of rainfall. However, the influence of rainfall in the later stage mainly comes from the accumulation of pore water pressure, which is not dissipated effectively in the early stage of rainfall.

Figure 8 shows the distribution of pore water pressure in lines 1-1 and 1-1' at the different rainfall times. From Figure 8, it can be seen that the pore water pressure in line 1-1' is larger than that in line 1-1 at the same rainfall time. The pore water pressure in line 1-1 and line 1-1' is larger than 0 kPa after $t = 9h$ and $t = 4.5h$, respectively, indicating that the layer transition zone has a significant influence not only on the pore water pressure distribution but also on the evolution process of pore water pressure. On the one hand, the transient saturation zone in the multilayered slope with the layer transition zone forms more rapidly than without the layer transition zone, which leads to a rapid accumulation of infiltrated water and a significant increase in pore water pressure. On the other hand, the rainfall recharge is greater than the discharge at the toe of the slope after the transient saturation zone is formed, which causes further increase in the pore water pressure and generation of excess pore water pressure. Therefore, in Figure 8, the soil saturated faster at line 1-1' than at line 1-1 and the excess pore water pressure is generated after saturation at line 1-1'. This indicates that the rapidly forming transient saturation zone caused by the layer transition zone accelerates the rate of increase of the pore water pressure and shortens the formation of the excess pore water pressure.

4.3. Influence of Layer Transition Zone on Stability of Multilayered Soil Slope. Figure 9 shows the distribution of the LFS in the multilayered slopes with and without the layer transition zone. Three specific time points (0h, 6h, and 15h) were selected to illustrate the influence of the transition zone on the stability of multilayered slopes. The initial conditions are the same for both the multilayered slopes with and without the layer transition zone. Based on the
calculated LFS under 1, the potential failure area is determined for all cases. The potential failure area is shown by the black line in Figure 9.

The main difference between two slopes is concentrated at the toe of the slope where it controls the stability of the entire multilayered slope. From Figure 9, it can be seen that the LFS at \( t = 6 \) h is lower for the multilayered slope without the layer transition zone than with the layer transition zone, indicating a more unstable condition. This can be attributed to the fact that the pore water pressure increases faster when the multilayered slope is without the layer transition zone. Therefore, at the same time of rainfall, there is a greater decrease in the effective stress. At the end of the rainfall, the rainfall infiltration has stabilized and the difference of pore water pressure in two multilayered slopes is smaller. For \( t = 15 \) h, the distributions of the LFS in two multilayered slopes are similar.

4.4. Critical Thickness of the Layer Transition Zone. Although previous studies have focused on the importance of a layer transition zone between soil layers, to our knowledge, the criteria of the layer transition zone are still unclear and need further discussion. If the thickness of the layer transition zone is large enough, it should be considered as an independent layer rather than a transition zone. The critical thickness of the layer transition zone is an essential problem. In this study, we emphasized that the criteria were not only the influence of the layer transition zone on the permeability but also the stability of the multilayered slope. In other words, the permeability of the entire multilayered slope with a critical thickness of the layer transition zone should be almost the same as the permeability of the entire multilayered slope without the layer transition zone. However, the stability of the entire multilayered slope with a critical thickness of the layer transition zone was significantly changed, compared to the multilayered slope without the layer transition zone. Thus, the transition zone between layers should be defined as a layer transition zone rather than an independent layer. If the thickness of the layer transition zone exceeds the critical thickness, both the permeability and stability of the multilayered slope change significantly, compared to the multilayered slope without the layer transition zone. In this case, it is more reasonable to consider this layer transition zone as an independent soil layer.

Since the permeability of the multilayered slope with a layer transition zone is lower than without a layer transition zone, the decreases in permeability as a function of the thickness ratio of the layer transition zone are calculated and shown in Figure 10. It can be seen that when the thickness ratio of the layer transition zone is 50%, the permeability reduced by 25%. Depending on the proposed criteria of the layer transition zone, for this case, the layer transition zone can be considered as an independent layer. The evolution of failure area during rainfall was calculated to investigate the critical thickness of the layer transition zone. It was found that at the same time of rainfall, there was a larger failure area in multilayered slope with a layer transition zone than without the layer transition zone. The increase in failure area of multilayered slopes with a layer transition zone as a function of the increment of permeability of multilayered slope is shown in Figure 10.

From Figure 9, it can be seen that when the thickness ratio of the layer transition zone is 2%-5%, the failure area of the slope increases significantly. Although the permeability decreases only by 1.0%-2.5%, the relative increase reaches about 25%. In the cases where the thickness ratio of the transition zone is 10.0%-50.0%, the failure area increases significantly. However, the variation of the permeability of the slope is more than 5% and reaches up to 25%, which indicates that it is inappropriate to consider this transition zone as a layer transition zone. Therefore, considering the influence of both permeability and stability of the multilayered slope, the critical thickness ratio of the layer transition zone is 5.0%.

5. Summary and Conclusion

In this study, a multilayered slope consisting of a sandy loam layer and a clay layer was constructed to investigate the influence of the layer transition zone on the rainfall-induced instability of the multilayered soil slope. The rainfall infiltration processes were numerically simulated in one multilayered soil slope without layer transition zone and
eight multilayered soil slopes with layer transition zone of different thickness ratios. The rainfall infiltration process, pore water pressure distribution, and LFS of multilayered soil slope with and without layer transition zone were compared and analyzed. In addition, the critical thickness of the layer transition zone was introduced and determined. The main conclusions are as follows:

1. The layer transition zone decreased the permeability of multilayered soil slope and reduced the discharge capacity of the slope. Under the same rainfall condition, the formation and expansion of the transient saturation zone were faster for the multilayered slope with a layer transition zone. However, due to the almost same permeability, the layer transition zone had little influence on the advancing depth of wetting front under the rainfall infiltration.

2. The layer transition zone had a significant influence on the distribution and evolution of pore water pressure. Under the same rainfall conditions, the pore water pressure at the toe of the multilayered soil slope was greater with a layer transition zone than without a layer transition zone. The layer transition zone accelerated the rate of increase of pore water pressure and shortened the generation time of the excess pore water pressure, resulting in a rapid decrease of LFS at the toe of the slope.

3. The critical thickness ratio of the layer transition zone was determined based on the fact that the layer transition zone basically had no influence on the permeability, but had a significant influence on the stability of the slope. For the multilayered slope, the critical thickness ratio of the layered transition was proposed as 5.0%. In the cases where the thickness...
ratio of the layer transition zone was 5.0%, the permeability decreased only by 2.5% while the increase in failure area was up to 25%

Since the multilayered slopes are ubiquitous in nature due to the geological deposition process, our result highlights the importance of the layer transition zone for the rainfall-induced instability of the multilayered slope. The proposed critical thickness ratio of the layer transition zone could not only distinguish the layer from transition zone and the independent layer but also determine the presence of layer transition. However, our current work focused on the two-dimensional numerical case, further study should investigate the influence of layer transition zone on the rainfall-induced instability of the in situ three-dimensional multilayered slopes.

Data Availability

All data, models, and code generated or used during the study appear in the submitted manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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