Stability Analysis of Unsaturated Red Clay Slope under Different Heavy Precipitation Patterns

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Abstract. A fluid-solid coupling numerical model was established for unsaturated red clay, which is prone to causing clustered landslides under three typical heavy precipitations in southwest China, to investigate the influence of the precipitation patterns on the infiltration mode, pore water pressure and stability of unsaturated red clay slopes. The investigation showed that (1) during heavy precipitation, much rainwater tends to form a transient saturated zone in the shallow layers of the slopes in a short time, thereby reducing the matric suction of the soil matrix; (2) under short-term continuous rainstorm, the pore water pressure dropped to the greatest extent; and (3) the safety factor experienced the largest decrease under persistent heavy precipitation following 24-hour rainfall, while slopes displaced the most under sudden rainstorm.

1. Introduction
In China, where geological disasters occur frequently, extreme precipitation is subject to increasing intensity and dominates in the total precipitation. In 2019, the country witnessed a total of 6,181 geological disasters, of which 4,220 were landslides, accounting for 68.3% of the total. Southwest China is the most severely afflicted area of landslide disasters due to its complex terrain, mountainous and hilly land, abundant precipitation and concentrated distribution of red clay [1]. Rainstorm is among the key factors behind landslide disasters which are prevalent under short-term extreme precipitation. According to the geological disaster investigation in 290 Chinese counties and cities, rainfall-induced landslides account for 90% of the total landslides [2]. Precipitation during the flood season, which lasts from May to September under the monsoon climate and the El Nino-Southern Oscillation, makes up more than 70% of the total rainfall, including 20% in 1-2 weeks [3]. Such short-term heavy precipitation infiltrates rainwater into side slopes, and leads to a rapid decline in matric suction, the disappearance of negative pore water pressure in the unsaturated zone and a decrease in shear strength, hence a landslide. Thus, given the same amount of precipitation, the precipitation patterns play a critical role in precipitation infiltration [4], and the occurrence of landslide is closely associated with the precipitation pattern and intensity.

Red clay in Southwest China, generally characterized by high swelling, high shrinkage, high engineering sensitivity and poor engineering properties, often cause landslide clusters. In dry condition, red clay slopes present slope fracture development, high soil strength, and great slope stability due to the effects of drying and wetting cycles; In water-rich condition, the slopes are prone to closed fractures, markedly decreased soil strength, deformation and instability [5].
Studies have been conducted on slope stability under different precipitation patterns. Tsai [6] modeled one-dimensional infiltration of water in soils to study the influence of precipitation patterns on shallow landslide and slope failure; Kim et al. [7] strongly linked slope failure to transient seepage of unsaturated soil slopes induced under different precipitation patterns; Jaesung et al. [8] evaluated the stability of an agricultural embankment under five precipitation patterns; And Ng et al. [9] categorized the precipitation profiles into four groups: uniform rainfall, post-peak rainfall, pre-peak rainfall and median rainfall.

These studies, however, focus mostly on stability analysis of homogeneous soil slopes under common rainfall types, leaving aside the seepage and stability of unsaturated red clay slopes in Southwest China under different heavy precipitation patterns. In such case, this paper was designed to summarize three heavy precipitation patterns causing large-scale landslides in Southwest China, fit several measured soil-water characteristic curves of red clay using MATLAB plotting, and establish a two-dimensional soil slope model by ABAQUS. Then, the infiltration and stability of unsaturated red clay slopes were explored under the heavy precipitation patterns, considering the water-force coupling.

2. Theory and numerical calculation

2.1. Seepage equations of unsaturated soils

Seepage equations of unsaturated soils include the soil-water characteristic curve (SWCC) and permeability coefficient equations, which represent the changes in volume water content-matrix suction and permeability coefficient-matrix suction respectively. To characterize unsaturated red clay soils in Southwest China, the measured data of the soils [10] were put into the Variance Gamma (Vg) Model showing high applicability of unsaturated clay, and the five parameters were worked out by MATLAB nonlinear fitting function Lsqcurvf it to fit the SWCC. Subsequently, the obtained parameters were substituted into Equations (2) and (3) to obtain the solution of the equation between the moisture absorption curve and the permeability curve. Finally, the solution was input into the material definition module of ABAQUS to assign seepage properties to the slope for fluid-solid coupling analysis.

SWCC in VG model was expressed as:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha \phi)^n]^{m}}$$  \hspace{1cm} (1)

Relationship between saturation and matric suction is:

$$S = \frac{1}{[1 + (\alpha \phi)^n]}$$ \hspace{1cm} (2)

Relationship between permeability coefficient and saturation is:

$$K_v = K_s \frac{S^n}{[1 - (1 - S^{n+1})^m]}$$ \hspace{1cm} (3)

Where $\theta$ is volume water content of soil;

- $\phi$ is matrix suction;
- $\theta_s$ is soil water content in saturated volume;
- $\theta_r$ is soil water content in residual volume;

S is saturation;

- $K_v$ is permeability coefficient of unsaturated soil;
- $K_s$ is saturated permeability coefficient; and

$\alpha$, $n$ and $m$ are fitting parameters, among which $m = 1-1/n$.

The parameters of the VG model were shown in Table 1. The moisture absorption curve (a) and permeability curve (b) were illustrated in Figure 1.
Table 1. VG Model Calculation Parameters

| $\theta_1$ | $\theta_2$ | $K_s$(cm/s) | $\alpha$ | $n$ |
|------------|------------|-------------|----------|-----|
| 0.5385     | 0.2628     | $6.77 \times 10^{-5}$ | 0.1640   | 1.5444 |

Fig. 1. Unsaturated Red Clay Seepage Control Equation
a. moisture absorption curve b. permeability curve

2.2 Finite element strength reduction technique
The finite element strength reduction method is in essence an approach to reduce shear strength indexes, i.e. cohesion and friction angle, by the Shear Strength Reduction Factor (SSRF), so as to lower the shear strength of soil. By definition, the SSRF is the ratio of the maximum soil shear strength of a slope to the actual shear stress when an external load applied to the slope remains constant.

In case all parts of the slope share the shear strength, the shear stress from the external load is equal to the actual shear strength after reduction when the slope is in limit equilibrium, and the value of SSRF ($Fr$) is taken as the safety factor of the slope ($Fs$).

By defining $Fr$ in the Property module, the cohesion and friction angle reduced with the change of field variables were obtained. Then $Fr$ is increased until the Property module did not converge, and the $Fr$ value was the value of $Fs$.

2.3 Finite element model and parameters
A two-dimensional slope model was constructed in ABAQUS to study the influence of heavy precipitation patterns on pore water pressure distribution of unsaturated red clay slopes and the change of slope stability during precipitation infiltration.
In the finite element model (Figure 2), AB, BC and CD were precipitation boundaries with the boundary function expressed by precipitation intensity $q$, and the slope angle is $\beta$. Here, rainfall fell vertically to the soil surface on AB and CD, the infiltration intensity on the slopes was 0.025 m/h, equal to the precipitation intensity, and the infiltration rate $I$ of Slope BC shares the figure (0.018 m/h) with the normal component of precipitation intensity ($I = q \cos \beta$).

AG and DE fix their horizontal displacements to 0, while GE fix both its horizontal and vertical displacement to 0. With initial groundwater level at the slope toe, the hydrostatic pore pressure of DE increased linearly with depth, i.e. $10 \times (10 - y)$, the pore pressure of CD was 0, and the remaining boundaries were undrained. Physical and mechanical parameters were shown in Table 2.

![Fig. 2. Unsaturated Red Clay Slope Finite Element Model](image)

|                | Dry density $\rho_c$ (g m$^{-3}$) | Cohesion $c$/kPa | Friction angle $\phi$/° | Initial void ratio $e_0$ | Elastic modulus $E$/Mpa | Poisson's ratio $\mu$ |
|----------------|-----------------------------------|------------------|-------------------------|--------------------------|------------------------|----------------------|
|                | 1.30                              | 30               | 15                      | 0.84                     | 10                     | 0.3                  |

### 3. Parameter analysis

#### 3.1. Influence of heavy precipitation patterns on pore water pressure distribution on slope

Based on the characteristics of rainfall intensity in the heavy precipitation-concentration period from May to September in Bazhong, Sichuan Province, three typical heavy precipitation patterns: persistent heavy precipitation, sudden rainstorm and continuous rainstorm were selected for subsequent analysis. Combined with the features of precipitation time-history classification in China, the three patterns had their time-history changes briefed in Figure 4, with the same total precipitation of 480 mm. Afterwards, an analysis was performed on how these patterns affected the distribution of pore water pressure along the depth direction of the slope within 24 hours.

![Fig. 3. Time history changes of the three types of heavy precipitation](image)

a. persistent heavy precipitation  
b. sudden rainstorm  
c. continuous rainstorm
Figure 5 illustrated that under the three patterns, the pore water pressure resumed its linear change at a depth of 20 m, which verified the condition that groundwater is below the slope toe. Without precipitation, the pore water pressure presented a linear distribution under hydrostatic pressure. In the early stage of precipitation, when \( t = 6 \) h, the pore water pressure at the slope crest rose the fastest under continuous rainstorm, from -200kPa to -58kPa, similar to that under persistent heavy precipitation but much higher than that under sudden rainstorm. As time went on, the pore water pressure under persistent heavy precipitation and continuous rainstorm changed less, while that under sudden rainstorm varied greatly.

As for main reasons, persistent heavy precipitation and continuous rainstorm brought large amount of precipitation when \( t < 6 \) h, at which time the precipitation intensity was larger than the infiltration rate of red clay with poor soil permeability. As a result, a transient saturated zone was formed in the shallow layer of the slope in a short time, the negative pore water pressure gradually disappeared, and the matrix suction approximated zero. The early stage of the sudden rainstorm, on the other hand, was characterized by low rainfall and less rainfall intensity than the infiltration rate of red clay, and the wetting front moved downward through the soil.

3.2. Influence of heavy precipitation patterns on displacement increment
The location of a potential slip surface was determined using the displacement increment nephograms of unsaturated red clay slopes under the three heavy precipitation patterns (Figure 5). The potential
slip surface was arc-shaped, and it was the least deep under persistent heavy precipitation, while the largest displacement increment with the largest change range under sudden rainstorm, mainly in the middle and upper part of the slope. This revealed that persistent heavy rainfall is most likely to cause shallow landslides, whilst sudden rainstorm is prone to triggering deep large-scale landslides.

This is mainly because the instantaneous rainfall of the early persistent heavy precipitation far topped the infiltration capacity of the soil. At this juncture, the permeability coefficient changed little, but the matric suction of the shallow layer decreased rapidly, so the rain could induce a shallow landslide although it failed to penetrate deep into the slope. Under sudden rainstorm, despite low rainfall in the early stage, the rainwater was infiltrated into a wide range of soil, which was prone to triggering plastic strain in the depth of the slope and thus deep landslide.

3.3. Influence of heavy precipitation patterns on slope stability

ABAQUS was used to process Combine Function provided by patterns. The evaluation standard was that the safety factor of slope crest did not converge with horizontal displacement. The curve of the safety factor is obtained and shown in Figure 6.

As can be seen from Figure 6, the safety factor of the slope decreased with precipitation infiltration, with the greatest change under persistent heavy precipitation, followed by continuous rainstorm and sudden rainstorm. At the point of 6 hours, the safety factor of sudden rainstorm with less accumulative rainfall decreases most rapidly and then slows down. During the first 6 hours, the safety factor curve of continuous rainstorm is flatter. After the 6-hour point, the safety reserve decreases more quickly and its overall decreasing trend is close to the continuous rainstorm, but the amplitude of its variation is close to the sudden rainstorm within 24 hours.

4. Conclusion

By ABAQUS, a two-dimensional soil slope model was established on the measured soil-water characteristic curves of unsaturated red clay fitted in MATLAB in this paper. Considering the fluid-solid coupling, the precipitation infiltration and stability change were investigated in widely-distributed red clay slopes under three heavy precipitation patterns in Southwest China and concluded that:

(1) A transient saturated zone formed in the shallow layer of red clay slope under all the three patterns, reducing the matrix suction in a very short time and thus quickly lowering the shear strength of soil.

(2) Heavy precipitation patterns have a significant impact on precipitation infiltration in red clay slopes, of which continuous rainstorm contributed the most to pore water pressure of unsaturated red clay slope, especially that at the slope crest within the first six hours of precipitation, which was likely to form a transient saturated zone in shallow layer.

(3) The three heavy precipitation patterns moved significantly different towards the time-history changes of the safety factor, which changed the fastest, decreased the most, and induced the greatest risk of slope instability under persistent heavy precipitation.

(4) Persistent heavy precipitation induced the least deep slip surface in the shallow layer, while sudden rainstorm was subject to the deepest slip surface with the largest displacement. It indicated that
sudden rainstorm is more likely to infiltrate rainwater into the deep layer of soil slope, causing deep slip and large-scale landslide disasters.

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