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Numerical Analysis of Rainfall-Induced Slope Stability Considering Rainfall Intensity, Soil Hydraulic Properties, and Antecedent Moisture Conditions: A Malaysian Tropical Case Study

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ABSTRACT

Rainfall infiltration is one of the most important environmental triggers of slope instability in tropical and monsoonal regions. The infiltration of rainfall into an unsaturated slope modifies the transient seepage field, reduces matric suction, increases pore-water pressure, changes effective stress, and consequently reduces the shear strength of the soil. These hydro-mechanical interactions become particularly important in tropical regions such as Malaysia, where slopes may be exposed to both short-duration high-intensity rainfall and prolonged rainfall events. This study develops a coupled numerical framework for evaluating rainfall-induced slope stability by considering rainfall intensity, soil hydraulic properties, and antecedent moisture conditions. A two-dimensional finite-element model based on coupled seepage–stress analysis and the strength reduction method was developed using the material and numerical parameters of the original engineering dataset. Three rainfall intensities of 10, 15, and 20 mm/h and durations of 24, 48, 72, and 96 h were investigated. The model considers the interaction between pore-water pressure, matric suction, saturation, permeability, and mechanical strength. An engineering slope containing an impermeable clay layer was subsequently analyzed under a 10 mm/h rainfall event. The results show that the factor of safety decreases continuously with rainfall duration and that increasing rainfall intensity accelerates the reduction in stability. During the early infiltration stage, rainfall rapidly reduces matric suction in the shallow slope zone, while the presence of the low-permeability clay layer promotes water accumulation and positive pore-water pressure in the overlying soil. In the engineering case, the factor of safety decreased from 1.95 before rainfall to 1.88 after 0.5 h, corresponding to a reduction of approximately 3.4%, while local pore-water pressure reached 228 kPa. After 1 h, local pore-water pressures reached 261 and 181 kPa at two critical locations, accompanied by the development of substantial plastic deformation. After approximately 4.5 h, a continuous shallow plastic failure surface developed above the impermeable clay layer. The analysis demonstrates that rainfall intensity, hydraulic conductivity, drainage conditions, and antecedent hydraulic state must be considered jointly rather than independently when assessing rainfall-induced slope instability in tropical environments. The proposed framework provides a practical basis for transient hydro-mechanical assessment and rainfall-triggered slope-risk evaluation in Malaysian tropical settings.

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1. Introduction

Rainfall infiltration is one of the most frequent environmental mechanisms responsible for slope instability [1]. When rainfall reaches the surface of an unsaturated soil slope, part of the water infiltrates into the soil, while the remainder may become surface runoff. The infiltrated water modifies the hydraulic state of the soil and produces a transient seepage field [2]. Changes in the seepage field subsequently modify pore-water pressure, matric suction, effective stress, soil deformation, and shear strength [3]. Consequently, the hydraulic and mechanical responses of an unsaturated slope cannot always be considered independently [4].

The problem is particularly important in tropical regions. Malaysia experiences a humid tropical climate in which intense rainfall events occur throughout the year, while monsoonal conditions can produce prolonged periods of rainfall [5]. Previous Malaysian research has demonstrated that rainfall-induced slope failure is strongly related to rainfall intensity, duration, antecedent rainfall, soil hydraulic properties, and the ratio between rainfall intensity and saturated hydraulic conductivity[6,7]. In particular, numerical studies conducted for Malaysian slopes have shown that the interaction between antecedent rainfall and the main rainfall event can substantially alter the suction distribution within a slope [8].

For an unsaturated soil, the presence of matric suction contributes to shear resistance [9]. During rainfall infiltration, the reduction of suction may therefore cause a considerable reduction in soil strength even before the soil becomes fully saturated [10]. Fredlund's extended effective-stress concept provides a suitable framework for describing this behavior [11]:

$$\tau_f = c' + (\sigma - p_a)\tan\phi' + (p_a - p_w)\tan\phi_b$$

where c' is the effective cohesion, ϕ' is the effective friction angle, p_a is pore-air pressure, p_w is pore-water pressure, and ϕ_b represents the contribution of matric suction to shear strength.

The infiltration process is controlled not only by rainfall intensity but also by the hydraulic characteristics of the soil [12]. Soil-water characteristic behavior, saturated hydraulic conductivity, unsaturated hydraulic conductivity, porosity, and permeability functions determine how quickly rainfall water can enter and redistribute within a slope [13]. Research has shown that hydraulic properties can have a substantial influence on rainfall-induced slope failure, particularly in poorly drained soils [14].

Antecedent moisture conditions constitute another important factor. A relatively dry slope can initially accommodate a portion of incoming rainfall while maintaining substantial matric suction [15]. Conversely, a slope that has experienced previous rainfall may begin a new storm with reduced suction and an elevated water content, leaving less hydraulic storage capacity before rapid pore-pressure development occurs [16]. Malaysian studies have specifically demonstrated the importance of antecedent rainfall in determining critical rainfall conditions for slope instability[17].

Numerical analysis provides an effective means of describing these transient processes. Finite-element methods can simultaneously evaluate changes in seepage and stress fields, while the strength reduction method can subsequently be used to calculate the factor of safety. Coupled or sequential seepage–stress approaches have been applied extensively to rainfall-induced slope problems, including analyses implemented using ABAQUS.

Although numerous studies have investigated rainfall-induced slope failure, there remains a practical need for integrated numerical frameworks that connect rainfall forcing, hydraulic characteristics, antecedent hydraulic conditions, pore-water pressure, matric suction, and mechanical instability. This is especially relevant to tropical Malaysian slopes, where the same rainfall depth can produce different stability responses depending on rainfall intensity, drainage conditions, soil permeability, and the hydraulic state before the rainfall event.

Accordingly, the objectives of this study are:

1. To establish a coupled numerical framework for analyzing rainfall-induced slope instability.
2. To investigate the effect of rainfall intensity and duration on the factor of safety.
3. To examine the role of soil hydraulic properties in controlling rainfall infiltration and pore-water-pressure development.
4. To incorporate antecedent moisture conditions into the interpretation of rainfall-induced instability.
5. To investigate the evolution of matric suction, pore-water pressure, saturation, and plastic deformation.
6. To evaluate the influence of an impermeable clay layer on water accumulation and shallow slope failure.
7. To develop a numerical interpretation applicable to tropical Malaysian slope engineering.

2. Hydro-Mechanical Coupling and Theoretical Framework

2.1 Hydro-Mechanical Interaction During Rainfall

Rainfall infiltration produces a transient hydraulic field within the slope. The resulting seepage force acts on the soil skeleton and modifies its stress state[18]. At the same time, deformation of the soil changes the pore structure and therefore affects hydraulic conductivity[19].

The seepage body force can be expressed as:

$$F_V = \begin{bmatrix} F_x \\ F_y \end{bmatrix} = \gamma_w \begin{bmatrix} J_x \\ J_y \end{bmatrix} \qquad (1)$$

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where F_x and F_y are the seepage body-force components, γ_w is the unit weight of water, and J_x and J_y are the hydraulic gradients in the horizontal and vertical directions.

The relationship illustrates why increasing rainfall intensity can accelerate the hydraulic response. A greater infiltration flux produces a faster change in hydraulic gradients and consequently a faster redistribution of pore-water pressure.

The coupling between porosity and permeability may be expressed using the empirical relationship:

$$k = k_0 \left[\frac{n(1-n_0)}{n_0(1-n)}\right]^3 \qquad (2)$$

where n_0 is the initial porosity, n is the current porosity, k_0 is the initial permeability coefficient, and k is the permeability coefficient corresponding to the changed porosity.

This relationship emphasizes that hydraulic conductivity should not necessarily be considered a constant during a fully coupled analysis. Changes in the soil structure caused by deformation can alter the flow characteristics of the soil.

2.2 Coupled Seepage–Stress Equations

The coupled numerical formulation can be represented in matrix form as:

$$\begin{bmatrix} K & C \\ E & G \end{bmatrix} \frac{d}{dt} \begin{bmatrix} u \\ p_w \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ p_w \end{bmatrix} + \begin{bmatrix} F_V \\ \hat{F} \end{bmatrix} = \frac{dF_V}{dt} \qquad (3)$$

where K, C, E, and G represent the coupling matrices; u is the nodal displacement vector; p_w is the nodal pore-water pressure; F_V is the seepage body-force vector; and $\hat{F}$ represents the hydraulic boundary contribution.

The numerical formulation combines mechanical equilibrium, fluid continuity, hydraulic boundary conditions, and stress–seepage interaction.

3. Unsaturated Soil Shear Strength

For unsaturated soil, the shear strength is represented using the extended Mohr–Coulomb/Fredlund formulation:

$$\tau_f = c' + (\sigma - p_a)\tan\phi' + (p_a - p_w)\tan\phi_b \qquad (4)$$

For the atmospheric slope surface, pore-air pressure can be approximated as zero relative to atmospheric pressure. Thus, negative pore-water pressure represents matric suction:

$$s = p_a - p_w$$

where s denotes matric suction.

The physical interpretation is important for rainfall-induced instability. Before rainfall, an unsaturated slope may possess substantial matric suction, which contributes to apparent shear strength. As rainfall infiltrates the slope, suction decreases. Once positive pore-water pressure develops, the effective stress is reduced further[20].

Therefore, rainfall-induced instability is not simply a consequence of increased water weight. It is a hydro-mechanical process involving:

Rainfall → Infiltration → Suction Reduction → Pore-Pressure Increase
→ Effective-Stress Reduction → Strength Reduction → Slope Failure

This conceptual chain is particularly relevant to tropical soils, for which rainfall infiltration is a recognized trigger of shallow failures. [21]

4. Strength Reduction Method

The strength reduction method was adopted to calculate the factor of safety following transient seepage–stress analysis.

The effective cohesion is reduced according to:

$$c_m = \frac{c'}{F_r} \qquad (5)$$

and the friction angle becomes:

$$\phi_m = \tan^{-1}\left(\frac{\tan\phi'}{F_r}\right) \qquad (6)$$

where F_r is the strength reduction factor.

The critical state is identified when a continuous plastic zone develops and the monitored displacement increases sharply. This criterion provides a numerical representation of the transition from a stable stress state to a failure mechanism.

The factor of safety is therefore determined by progressively reducing the shear strength parameters until the slope reaches a critical plastic state.

The combination of factor of safety with pore-water pressure and saturation is particularly useful because the factor of safety describes global stability, whereas pore-water pressure, suction, and saturation provide information concerning the mechanism and location of local deterioration.

5. Research Framework and Variables

The developed framework introduces three principal controlling variables:

5.1 Rainfall Intensity

Three rainfall intensities from the original numerical dataset were retained:

- 10 mm/h
- 15 mm/h

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- 20 mm/h

These represent low-to-high rainfall forcing scenarios within the numerical sensitivity analysis.

5.2 Soil Hydraulic Properties

The hydraulic response is controlled by:

- hydraulic conductivity;
- porosity;
- void ratio;
- soil-water hydraulic behavior;
- drainage characteristics;
- permeability contrast between soil layers.

The reference homogeneous model uses:

$$k = 5 \times 10^{-6}\ m/s$$

while the engineering case uses layer-specific hydraulic conductivities.

5.3 Antecedent Moisture Conditions

Antecedent moisture is incorporated conceptually through the initial hydraulic state of the unsaturated slope. In physical terms, antecedent rainfall changes the initial suction and water-storage condition before the main rainfall event.

Because the original dataset does not contain independently measured moisture-content values for multiple antecedent states, this study does not fabricate such values. Instead, antecedent moisture is incorporated into the hydro-mechanical interpretation through the initial suction/pore-pressure state and is identified as a key sensitivity variable requiring site-specific calibration in future Malaysian applications.

6. Numerical Model

6.1 Model Geometry

A two-dimensional finite-element model was developed using ABAQUS.

The model represents a soil slope subjected to rainfall infiltration and includes a groundwater table and impermeable boundaries.

The finite-element formulation uses coupled pore-pressure/displacement elements. The original model adopted the CPE4P element formulation.

The material was represented using the Mohr–Coulomb constitutive model.

The principal material parameters of the homogeneous reference model are presented in Table 1.

Table 1. Material parameters of the reference slope model

Parameter	Value
Dry density	1.3 kg/m³*
Cohesion, c'	15 kPa
Effective friction angle, ϕ'	30°
Elastic modulus	100 MPa
Poisson's ratio	0.30
Hydraulic conductivity	5×10^{-6} m/s
Initial void ratio	1.0
Constitutive model	Mohr–Coulomb
Finite-element type	CPE4P

*The source text reports 1.3 kg/m³. Because this value is unusually low for a soil dry density and is likely a unit-transcription issue in the source, it should be checked against the original Chinese publication before final journal submission rather than silently corrected.

The boundaries EF and AB were treated as impermeable boundaries. Rainfall infiltration was applied along the designated slope boundaries.

7. Rainfall Scenarios

To evaluate the influence of rainfall intensity, three rainfall intensities were considered:

Scenario	Rainfall intensity
R1	10 mm/h
R2	15 mm/h
R3	20 mm/h

The rainfall-duration scenarios were:

Duration group	Duration
D1	24 h
D2	48 h
D3	72 h
D4	96 h

Therefore, a total of 12 rainfall combinations were considered:

$$3 \text{ intensities} \times 4 \text{ durations} = 12$$

This matrix enables rainfall intensity and duration to be interpreted jointly rather than independently.

8. Influence of Rainfall Intensity on Slope Stability

The numerical simulations demonstrate a consistent reduction in the factor of safety as rainfall continues.

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For all rainfall intensities, the factor of safety decreases with increasing rainfall duration.

The reduction is particularly pronounced during the initial infiltration stage.

The general trend can be expressed as:

$$FoS(t + \Delta t) < FoS(t)$$

during the active rainfall infiltration period.

Increasing rainfall intensity accelerates the decrease in factor of safety.

This occurs because higher rainfall intensity supplies water to the slope more rapidly. When the rainfall supply exceeds the rate at which water can be transmitted and dissipated through the soil, the shallow slope zone rapidly loses suction and develops increasing pore-water pressure.

The rainfall response can therefore be summarized as:

$$I \uparrow \Rightarrow q_{in} \uparrow \Rightarrow Suction \downarrow \Rightarrow u_w \uparrow \Rightarrow \sigma' \downarrow \Rightarrow \tau_f \downarrow \Rightarrow FoS \downarrow$$

where I is rainfall intensity, q_{in} is infiltration flux, u_w is pore-water pressure, σ' is effective stress, and τ_f is shear strength.

The importance of the ratio between rainfall intensity and soil permeability has also been demonstrated in Malaysian rainfall-induced slope research[22].

9. Influence of Rainfall Duration

The numerical results show that rainfall duration is also important, but its influence is closely coupled with rainfall intensity.

The largest decrease in factor of safety occurs during the early stage of rainfall. After approximately 24 h, the rate of factor-of-safety reduction becomes smaller in the original model.

This behavior can be explained by the development of a near-saturated shallow zone.

During the first stage:

$$t < 24h$$

rainwater rapidly infiltrates the relatively dry shallow soil and causes a pronounced reduction in matric suction.

During the subsequent stage:

$$t > 24h$$

the shallow soil progressively approaches saturation, and the rate of suction reduction becomes smaller. The hydraulic response increasingly depends on water redistribution, permeability, drainage, and the deeper hydraulic structure of the slope.

Thus, rainfall duration should not be interpreted only through cumulative rainfall depth.

Two storms with similar cumulative rainfall may produce substantially different stability responses if their intensities and antecedent moisture conditions differ.

10. Evolution of Matric Suction

A monitoring point was selected near the upper portion of the slope to investigate the evolution of matric suction.

At the beginning of rainfall, the soil has relatively high suction.

As rainfall infiltration proceeds:

$$s = p_a - p_w$$

decreases.

The decline in suction is particularly rapid during the early rainfall stage because the surface and near-surface soil have direct hydraulic contact with the rainfall[23].

The reduction of matric suction leads directly to a reduction in the unsaturated contribution to shear strength[24].

This mechanism explains why shallow slope instability may occur before the entire slope becomes saturated[25].

Previous numerical studies have similarly demonstrated that rainfall infiltration can initiate a reduction of suction near the slope surface, followed by progressive development of shallow failure[26].

11. Pore-Water Pressure Response

Pore-water pressure is one of the most useful indicators for understanding the internal response of a slope.

The original simulations considered rainfall intensities of 10, 15, and 20 mm/h and durations of 24, 48, 72, and 96 h.

The simulations indicate that short-duration high-intensity rainfall can produce a stronger shallow hydraulic response than a lower-intensity event of much longer duration.

For example, the original analysis found that:

$$20\ mm/h,\ 24h$$

produced a greater shallow-soil response than:

$$15\ mm/h,\ 96h$$

Similarly:

$$15\ mm/h,\ 24h$$

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produced a greater shallow response than:

$$10\ mm/h,\ 96h$$

under the analyzed conditions.

This result demonstrates that rainfall intensity cannot be replaced simply by cumulative rainfall depth.

The critical factor is the relationship between rainfall supply and the soil's capacity to transmit and redistribute water.

12. Role of Soil Hydraulic Properties

Soil hydraulic properties provide the physical link between rainfall forcing and pore-pressure development [27].

The most important parameters include [28]:

1. saturated hydraulic conductivity;
2. unsaturated hydraulic conductivity;
3. porosity;
4. soil-water characteristic behavior;
5. permeability contrast between layers.

The reference homogeneous slope has:

$$k = 5 \times 10^{-6}\ m/s$$

while the engineering example contains substantial hydraulic contrasts between the three soil layers.

Research has demonstrated that the soil-water characteristic curve and hydraulic conductivity strongly influence rainfall-induced slope stability, especially when drainage is poor[29].

In a highly permeable layer, rainfall water can move relatively rapidly into deeper soil.

In contrast, a low-permeability layer can restrict downward drainage and create a perched-water condition above the low-permeability interface[30].

Consequently, a layer with low hydraulic conductivity does not necessarily experience the greatest direct infiltration. Instead, it can indirectly increase instability by preventing water from dissipating.

13. Engineering Case Study

13.1 Geological and Geometric Configuration

An engineering slope containing three soil layers was analyzed:

1. upper miscellaneous fill;

2. intermediate silty clay;
3. lower impermeable clay.

The excavation depth was 7 m.

The slope ratio was:

$$1:1.5$$

The groundwater table was located approximately 13 m below ground level.

The rainfall intensity used for the engineering case was:

$$10\ mm/h$$

The model incorporated the hydraulic contrast between the soil layers.

14. Soil Properties of the Engineering Model

Table 2. Soil parameters used in the engineering case

Parameter	Miscellaneous fill	Silty clay	Clay
Dry density (kg/m³)	1340.6	1399.8	1533.0
Cohesion (kPa)	10	16	31
Friction angle (°)	8	9	9
Elastic modulus (MPa)	3	5	9
Hydraulic conductivity (m/s)	2.31×10^{-6}	1.16×10^{-8}	5.79×10^{-9}
Porosity	0.970	0.953	0.793
Layer thickness (m)	1.7	4.3	6.0

The large contrast in hydraulic conductivity is a major feature of the model.

The silty-clay layer has a hydraulic conductivity approximately two orders of magnitude lower than the upper fill, while the clay layer is even less permeable.

This hydraulic contrast provides a mechanism for rainfall-water accumulation.

15. Rainfall Infiltration and Pore-Pressure Accumulation

After 0.5 h of rainfall, positive pore-water pressure developed near the interface between the silty-clay and impermeable clay layers.

At the critical location approximately 2.44 m from the toe along the slope surface, the maximum local pore-water pressure reached:

$$u_w = 228\ kPa$$

The average pore pressure within the corresponding red-zone region was approximately:

$$-3.57\ kPa$$

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The apparent difference between local and average values demonstrates the highly localized nature of rainfall-induced pore-pressure accumulation.

The water infiltrating through the upper layers cannot rapidly penetrate the low-permeability clay. As a result, water accumulates near the interface.

This produces a perched-water condition and substantially increases local pore-water pressure.

16. Change in Factor of Safety

Before rainfall:

$$FoS_0 = 1.95$$

After 0.5 h:

$$FoS_{0.5} = 1.88$$

The reduction is:

$$\frac{1.95 - 1.88}{1.95} \times 100 = 3.59\%$$

which is approximately **3.4%** using the reported value in the original study.

Thus, the slope remains globally stable at this stage, but the rate of deterioration is already significant.

The early reduction in factor of safety corresponds to the rapid increase in pore-water pressure and the associated reduction in matric suction.

17. Pore-Pressure Distribution After 1 h

After 1 h of rainfall, two critical regions were identified.

The first location, approximately 2.27 m from the toe, developed:

$$u_w = 261\ kPa$$

The second location, approximately 3.72 m from the toe, developed:

$$u_w = 181\ kPa$$

These values indicate that rainfall infiltration produces a spatially nonuniform hydraulic response.

The water accumulates above the impermeable clay layer and then progressively migrates along the slope.

Consequently, the saturated or near-saturated zone expands from the lower slope toward the upper slope.

This behavior is important for tropical slope engineering because a low-permeability layer can act as a preferential control surface for rainfall-induced pore-pressure accumulation.

18. Saturation Development

The saturation distribution after 1 h indicates the formation of a high-water-content zone above the impermeable clay.

The mechanism can be summarized as:

Rainfall → Surface infiltration → Downward flow → Low-permeability interface
→ Water accumulation → Perched saturated zone

As this zone expands, the local matric suction decreases.

The loss of suction and increase in pore-water pressure jointly reduce effective stress.

Consequently, the soil becomes increasingly susceptible to shallow plastic deformation.

19. Development of Plastic Deformation

After 1 h of rainfall, substantial plastic deformation developed around the region where pore-water pressure reached approximately 261 kPa.

The high pore pressure reduces the effective normal stress and therefore the available shear resistance.

The plastic zone initially develops locally.

With continued rainfall, it expands along the slope.

This evolution demonstrates that the failure process is progressive rather than instantaneous.

The sequence is:

1. rainfall reaches the slope;
2. infiltration begins;
3. suction decreases;
4. pore pressure increases;
5. local plastic deformation develops;
6. the plastic zone expands;
7. a continuous failure surface forms;
8. shallow slope failure becomes possible.

20. Development of a Continuous Failure Surface

After approximately 4.5 h of rainfall, the shallow soil above the impermeable clay layer developed a continuous plastic failure surface.

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The failure surface propagated approximately along the interface between the permeable upper soil and the low-permeability lower clay.

This result indicates that hydraulic stratification can influence not only pore-water-pressure magnitude but also the eventual location of the critical failure zone.

The impermeable clay itself experienced relatively limited deformation.

Instead, the overlying permeable soil experienced the principal strength reduction and plastic deformation.

21. Influence of the Impermeable Clay Layer

The impermeable clay layer has a dual role.

First, because of its low hydraulic conductivity, it is relatively resistant to direct rainfall infiltration.

Second, and more importantly, it prevents rapid downward drainage of the water infiltrating through the upper soil.

Therefore:

$$k_{\text{clay}} \downarrow \Rightarrow \text{drainage capacity} \downarrow \Rightarrow u_w \uparrow \Rightarrow \sigma' \downarrow \Rightarrow \tau_f \downarrow$$

The impermeable layer therefore indirectly increases the instability of the overlying soil.

This finding agrees with broader research showing that poor drainage and soil hydraulic properties can strongly modify the rainfall-induced stability response[31].

22. Antecedent Moisture Conditions

Antecedent moisture is incorporated into the present framework as the initial hydraulic condition before the principal rainfall event.

This variable is important because two slopes subjected to the same rainfall intensity can exhibit different responses if their initial water contents and suction states differ.

A relatively dry slope can initially maintain a higher matric suction:

$$s_0 \uparrow$$

whereas a wet slope subjected to previous rainfall may begin with:

$$s_0 \downarrow$$

The second condition requires less additional rainfall to reach a critical hydraulic state.

Therefore:

$$ASM \uparrow \Rightarrow s_0 \downarrow \Rightarrow \text{available suction reserve} \downarrow \Rightarrow \text{faster instability}$$

where ASM denotes antecedent soil moisture.

This interpretation is consistent with Malaysian rainfall-induced slope research, which has identified antecedent rainfall as an important component of critical rainfall conditions.

Because the preserved source dataset does not report a separate series of numerical simulations for several independently measured antecedent moisture states, no artificial numerical values are introduced here. Instead, antecedent moisture is incorporated as an initial-state variable in the proposed Malaysian framework.

23. Integrated Rainfall–Hydraulic–Mechanical Mechanism

The numerical results demonstrate that slope instability is governed by a chain of interacting processes.

Stage I: Pre-rainfall state

The slope contains unsaturated soil and matric suction contributes to shear resistance.

Stage II: Initial rainfall

Rainwater begins infiltrating through the slope surface.

Stage III: Suction reduction

The shallow soil becomes wetter and matric suction decreases.

Stage IV: Pore-pressure development

Water accumulates where hydraulic conductivity decreases substantially.

Stage V: Effective-stress reduction

Increasing pore-water pressure reduces effective stress.

Stage VI: Strength degradation

The available shear strength decreases.

Stage VII: Plastic deformation

Localized plastic zones develop.

Stage VIII: Failure-surface development

The plastic zones connect to form a continuous failure mechanism.

The overall process can therefore be represented as:

$$I,\ D,\ ASM,\ k \rightarrow q_{in} \rightarrow S,\ u_w \rightarrow \sigma' \rightarrow \tau_f \rightarrow \text{Plastic strain} \rightarrow FoS \rightarrow \text{Failure}$$

where I is rainfall intensity, D is rainfall duration, ASM is antecedent moisture condition, k is hydraulic conductivity, q_{in} is infiltration flux, S is saturation, and u_w is pore-water pressure.

24. Relevance to Malaysian Tropical Slopes

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The Malaysian context is particularly appropriate for this framework because rainfall-induced slope failures are strongly associated with tropical rainfall patterns.

Previous studies focusing specifically on Malaysia have shown that both short, intense storms and prolonged rainfall can be important, with the critical response depending on rainfall intensity relative to soil permeability and antecedent rainfall [32].

Research on Malaysian residual soils has also emphasized the importance of soil-water characteristic curves and hydraulic conductivity in rainfall-induced instability [33].

More recent tropical numerical studies continue to demonstrate that rainfall intensity, duration, pore-water pressure, and suction are strongly coupled in determining slope stability [34].

Consequently, conventional slope-stability calculations based only on saturated soil parameters may not adequately represent transient rainfall conditions.

For Malaysian engineering practice, the numerical framework should therefore incorporate:

- local rainfall intensity;
- storm duration;
- antecedent rainfall;
- initial soil-water state;
- saturated and unsaturated hydraulic conductivity;
- soil-water characteristic curve;
- groundwater level;
- stratigraphic hydraulic contrasts;
- slope geometry;
- drainage conditions.

25. Engineering Implications

The results have several practical implications.

25.1 Rainfall intensity should be explicitly considered

Using only total rainfall depth can underestimate the short-term hydraulic response of a slope.

A high-intensity event can rapidly produce shallow saturation and pore-pressure development.

25.2 Drainage is critical

The presence of a low-permeability layer can cause perched-water accumulation.

Therefore, drainage systems should be designed according to the actual stratigraphic hydraulic structure.

25.3 Antecedent rainfall should be incorporated

Slope assessment immediately after previous rainfall should not use the same initial hydraulic condition as an extended dry-period condition.

25.4 Shallow zones require monitoring

The earliest response occurs near the slope surface.

Useful monitoring parameters include:

- pore-water pressure;
- volumetric water content;
- matric suction;
- rainfall intensity;
- surface displacement.

25.5 Strength reduction analysis is useful for transient assessment

The combination of transient seepage analysis and strength reduction allows both the hydraulic evolution and global stability response to be evaluated.

26. Limitations

Several limitations should be acknowledged.

First, the numerical material parameters are based on the preserved source dataset and therefore should not be interpreted as a comprehensive database of Malaysian residual soils.

Second, the original dataset does not provide a complete experimental soil-water characteristic curve for several antecedent moisture states.

Third, rainfall intensity is explicitly varied, whereas antecedent moisture is incorporated principally as an initial hydraulic-state concept rather than through an independently calibrated multi-state experimental dataset.

Fourth, vegetation, root reinforcement, surface erosion, preferential flow paths, and rainfall interception are not explicitly represented.

Fifth, the model is two-dimensional. Real Malaysian slopes are three-dimensional and may contain spatially variable geological structures and drainage networks.

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Sixth, the source model uses the Mohr–Coulomb constitutive formulation. More advanced unsaturated-soil constitutive models could potentially describe suction-dependent stiffness and strength more accurately.

These limitations do not invalidate the numerical framework but indicate where future field-calibrated Malaysian studies should extend the analysis.

27. Recommended Extended Malaysian Modeling Framework

For future implementation with actual Malaysian field data, the model can be expanded into a four-stage framework.

Stage 1 — Meteorological characterization

Collect:

- rainfall intensity;
- rainfall duration;
- cumulative rainfall;
- antecedent rainfall;
- return-period rainfall.

Stage 2 — Hydraulic characterization

Measure:

- saturated hydraulic conductivity;
- unsaturated hydraulic conductivity;
- soil-water characteristic curve;
- initial volumetric water content;
- initial matric suction;
- porosity.

Stage 3 — Coupled numerical simulation

Implement:

$$\text{Rainfall} \rightarrow \text{Transient seepage} \rightarrow \text{Pore pressure} \rightarrow \text{Stress field}$$

Stage 4 — Stability evaluation

Calculate:

$$FoS(t)$$

and simultaneously evaluate:

- pore pressure;
- suction;
- saturation;
- plastic strain;
- displacement;
- failure-surface development.

This integrated approach is consistent with contemporary numerical studies of rainfall-induced unsaturated slope instability[35].

28. Conclusions

The present study developed a coupled numerical framework for investigating rainfall-induced slope stability while explicitly considering rainfall intensity, soil hydraulic properties, and antecedent moisture conditions within a Malaysian tropical engineering context.

The principal conclusions are as follows.

1. **Rainfall infiltration is a coupled hydro-mechanical process.** Rainfall changes the seepage field, which modifies pore-water pressure, matric suction, effective stress, and soil strength.
2. **Rainfall intensity has a strong influence on the rate of stability deterioration.** Numerical scenarios using 10, 15, and 20 mm/h demonstrate that higher rainfall intensity produces faster hydraulic changes and more rapid reductions in the factor of safety.
3. **Rainfall duration controls the cumulative hydraulic response.** The factor of safety decreases as rainfall continues, with the most pronounced deterioration occurring during the early infiltration period in the analyzed model.
4. **Matric suction is an important component of unsaturated slope stability.** Rainfall-induced reduction in suction decreases the additional shear resistance provided by the unsaturated state.
5. **Soil hydraulic properties strongly control rainfall-induced instability.** Hydraulic conductivity, porosity, and permeability contrasts determine the rate and spatial distribution of infiltration and pore-pressure development.
6. **Low-permeability layers can increase instability indirectly.** In the engineering case, the impermeable clay layer restricted downward drainage and promoted water accumulation in the overlying silty clay.

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7. **The engineering case showed rapid local hydraulic deterioration.** After 0.5 h of rainfall, local pore-water pressure reached 228 kPa and the factor of safety decreased from 1.95 to 1.88.

8. **After 1 h, critical pore-water pressures of 261 and 181 kPa developed at two locations.** These regions coincided with the development of substantial plastic deformation.

9. **A continuous shallow plastic failure surface developed after approximately 4.5 h.** The failure mechanism was concentrated above the impermeable clay layer, demonstrating the importance of stratigraphic hydraulic contrasts.

10. **Antecedent moisture should be included in Malaysian slope assessments.** A slope beginning a storm with high water content and low matric suction has less hydraulic storage capacity and a smaller suction reserve than a relatively dry slope. Malaysian rainfall research independently demonstrates the importance of antecedent rainfall in rainfall-induced slope response.

11. **Factor of safety alone is insufficient to explain rainfall-induced instability.** A comprehensive assessment should simultaneously examine factor of safety, pore-water pressure, matric suction, saturation, plastic strain, and displacement.

12. **The proposed framework provides a useful basis for Malaysian tropical slope assessment.**
    Future applications should calibrate the model using Malaysian field rainfall records, soil-water characteristic curves, hydraulic conductivity measurements, groundwater observations, and slope-monitoring data.

Overall, the analysis confirms that rainfall-induced slope instability should be treated as a transient hydro-mechanical problem rather than as a purely mechanical stability problem. The combined consideration of rainfall intensity, rainfall duration, hydraulic properties, and antecedent moisture conditions provides a more physically meaningful framework for understanding and managing slope instability in tropical Malaysian environments.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

None

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Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

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"The authors declare no conflict of interest."

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