Comprehensive hydromechanical analysis of unsaturated heterogeneous slopes in the Tébessa region

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ABSTRACT
Landslides, triggered by the loss of soil cohesion, necessitate a thorough understanding of soil hydrological properties, particularly concerning rainfall. This study employs FLAC software for numerical modeling to examine a slope in the Tebessa region, focusing on the effects of precipitation infiltration, suction profiles, and slope heights on the safety factor. The hydraulic characteristics of unsaturated soil are represented using the van Genuchten equations. Initial analyses combine hydromechanical assessments across various soil layers to understand how rainfall infiltration influences deformation and pore-water pressure, thereby affecting slope stability. Stability evaluations are conducted before and after rainfall events. A second part of the study compares the results of the finite difference method (FDM) and the finite element method (FEM) using FLAC and PLAXIS software. To achieve an effective comparison, we explored various methodologies for analyzing two-dimensional slope models using different soil types exposed to varying precipitation levels. Coupled simulations, enabled by the two-phase flow option, are used to evaluate the stability of slopes in the unsaturated state. The validity of these methods is assessed by altering soil types and examining how varying suction values for each soil, hydraulic conductivity, and precipitation influence the safety factor. Results highlight the necessity of considering surface runoff infiltration and incorporating comprehensive soil layer attributes for accurate slope stability modeling. Discrepancies between the software packages at high suction values are noted, with FLAC being more conservative and superior in representing unfavorable conditions.
Keywords: Landslides, Hydromechanical Analysis, Finite Difference, Suction Profile.

1 INTRODUCTION

In regions characterized by rugged terrains and steep inclines, the looming threat of landslides triggered by rainfall is ever-present. These natural disasters, with their potential to devastate infrastructure and endanger lives, are influenced by various factors such as soil composition, terrain steepness, and rainfall intensity. Understanding how soil reacts to rainfall is pivotal in mitigating landslide risks, and researchers employ two primary methodologies: the Uncoupled Hydromechanical Model UCHM and the Coupled Hydromechanical Model CHM.

The uncoupled method involves dissecting how water permeates through the soil to anticipate water pressure, subsequently using this data to predict the soil deformations or slides. Conversely, the coupled approach intertwines water movement with soil changes, acknowledging their intertwined nature. This pursuit mirrors a complex puzzle that research diligently endeavors to unravel, striving to bolster safety measures amidst heavy rainfall in mountainous regions.

Prior research has significantly contributed to the field of unsaturated slope stability analysis, with notable studies delving into site-specific approaches and software-based simulations. For instance, Kang. S's (2020) investigation in Hwangryeong Mountain, South Korea, utilizing the CHM model, showcased superior simulation outcomes compared to other methods. Kang. S (2019) study applied the CHM model considering two-phase (water and air) flow to simulate rainfall infiltration and slope stability for Halmidang Mountain, using GIS-based data, geotechnical and hydrological properties, and historical rainfall data. The model evaluated changes in the safety factor at actual slope failure sites. Findings revealed that airflow and hydro-mechanical coupling significantly influence pore water pressure during rainfall infiltration, causing slower infiltration rates compared to the single-phase flow model, making the coupled model necessary for accurate simulations. The safety factor before rainfall is influenced by shear strength parameters, while the infiltration rate during rainfall strongly affects it. The coupled model shows larger increases in pore water pressure before ponding during weak rain, leading to a rapid decrease in safety factors, whereas the single-phase model leads to rapid saturation and lower final safety factors during heavy rain.

According to Mburu's (2022) study, which examines unsaturated silty slopes under steady infiltration, focusing on parameters affecting apparent cohesion and slope stability. The findings highlight the significance of water table location, infiltration rate, pore size, and slope height. The comparative analysis in Mburu's study of PLAXIS LE, Slide 2D (Uncoupled), and PLAXIS 2D (fully coupled) software
reveals differences in slope stability predictions. The study found that the fully coupled PLAXIS 2D model shows a lower critical Safety Factor, sharper wetting front, and shallower failure surface compared to other programs and the Hydraulic conductivity (ks) is identified as the main controlling parameter of the hydromechanical response and failure time of the unsaturated slope under rainfall infiltration.

Technological advancements have led to the widespread use of software to evaluate slope stability using various numerical analysis solutions. However, debates continue regarding the most effective approach for analyzing slope stability, especially in the case of unsaturated soils.

This article undertakes a comprehensive analysis of landslide risks in the Tébessa region. The primary objective is to examine the impact of different layers of unsaturated soils and slope heights under rainy conditions on slope stability. Additionally, the study aims to assess the influence of the soil-water characteristic curve (SWCC) using intact soils, and the intensity of rainfall on safety. Using various software tools, the results derived from different slope stability analysis programs are compared. By utilizing diverse software tools, this study compares the outcomes obtained from various slope stability analysis programs. To meet the study's goals, three unique soil types from the Tébessa region, each with distinct hydrological characteristics, are simulated and examined.

The study focuses on a specific slope located in Tebessa city, as depicted in the provided (Figure 1) and in accordance with the location map. The geological context of the site predominantly consists of sedimentary terrains comprising clay and sandstone formations.

These clays exhibit varying colors, such as black, green, or red, and they contain occasional thin layers of quartzite, small sandstone beds, and bluish marly limestone. Based on various indices,
observations, and visual assessments, compelling evidence supports the conclusion that the ground movement at the site is attributed to a rapid, circular plan landslide. This type of landslide occurs as a result of intense rainfall, which triggers soil destabilization and rupture along the slope. The primary factor contributing to this landslide event is the occurrence of severe weather conditions, specifically heavy and prolonged rainfall.

2 MATERIALS AND METHODS

2.1 SLOPES SIMULATION

The shear strength reduction method (SSRM) has been extensively employed by researchers for a range of applications. This method proves particularly beneficial in tackling challenges related to complex geometries, seepage analysis, consolidation, and the interaction between hydrological and mechanical behaviors. Its utilization frequently results in more effective solutions for these complex issues (Mburu et al., 2022). SSRM determines numerically the critical failure surface by calculating the failure shear strain zones that develop after changes in suction caused by rainfall over a specific period. In software such as PLAXIS 2D and FLAC 2D, the factor of safety (FoS) is determined using the shear strength reduction method (SSRM).

In FLAC (FDM), the analysis of unsaturated slopes integrates suction through constitutive models like the Soil Water Characteristic Curve (SWCC) and unsaturated soil shear strength parameters. Suction's impact on the safety factor in FLAC is influenced by explicitly representing soil-water-air interactions, enabling a thorough examination of moisture-induced alterations in soil behavior and its repercussions on slope stability. Conversely, PLAXIS utilizes a finite element method (FEM) for numerical analysis, concentrating on discretizing the soil domain into finite elements. PLAXIS provides diverse constitutive models to accommodate unsaturated soil behavior, including the Van Genuchten model for the soil-water retention curve. so, the study uses the Van Genuchten model as a soil-water behavior law to identify suction as a function of water content variation.

The development of a transient hydromechanical study necessitates the systematic integration of hydraulic (water flow) and mechanical (soil deformation) processes. Implementing this approach is crucial for accurately simulating and predicting slope failures caused by precipitation in unsaturated soil conditions. In unsaturated soil scenarios, the pore volume contains water partially, with the remaining fraction occupied by air, highlighting a fundamental disparity in defining effective normal stress between saturated and unsaturated soils. Shear strength is derived from the Mohr-Coulomb failure criterion and Terzaghi’s (1950) effective stress concept, as follows:
The capillary pressure law relates the difference in fluid pore pressures to saturation:

\[ P_c = P_a - P_w \]  \hspace{1cm} (2)

where:

- \( P_c \) is the capillary pressure,
- \( P_a \) is the pressure of the non-wetting fluid and,
- \( P_w \) is the pressure of the wetting fluid.

The pore spaces within the porous media are assumed to be completely filled by the two fluids, as expressed by Equation (3). The two fluids completely fill the pore space, \( S_w \) is the saturation of the wetting fluid, and \( S_a \) is the saturation of the non-wetting fluid, and we have:

\[ S_w + S_a = 1 \]  \hspace{1cm} (3)

Bishop’s effective stress is defined as Equation (4):

\[ \sigma'_b = (\sigma - P_a) + \chi (P_a - P_w) \]  \hspace{1cm} (4)

The matric suction coefficient can be replaced by the degree of saturation by replacing \( \chi \) with the degree of saturation (Hu, R., et al, 2018):

\[ \sigma'_b = \sigma - (P_w S_w + S_a P_a) \]  \hspace{1cm} (5)

A practical Equation (6) expresses the safety factor of unsaturated soil, incorporating parameters such as frictional resistance angle \( (\phi') \), pore air pressure \( (P_a) \), and pore water pressure \( (P_w) \).

\[
F_s = \frac{\tau_{\max}}{\tau_n} = \frac{(W \cos^2 \beta) \tan \phi' + (P_w S_w + S_a P_a) \tan \phi' + c'}{\tau_n}
\]  \hspace{1cm} (6)

where:
\( W \) is the weight of a soil slice, 
\( \beta \) is the slope angle, and 
\( \tau_n \) is the reduced shear strength that is just large enough to maintain equilibrium.

Matric suction refers to the discrepancy between pore air pressure and pore-water pressure within the soil. The correlation between soil water content and pore-water pressure is depicted through the soil-water characteristic curve (SWCC), illustrating volumetric moisture content against matric suction. A prevalent method for characterizing the hydraulic attributes of unsaturated soils is through a series of closed-form equations pioneered by van Genuchten (1980), which are rooted in Mualem's capillary model. The capillary pressure law is structured in the van Genuchten form, as follows:

\[
P_c = P_0 \left[ (S_e)^{-m} - 1 \right]^{1-m} 
\]  
\[ P_0 = \frac{\rho_w g \alpha}{\alpha} \]  

where:

- \( S_e \) is effective saturation;
- \( m \) and \( \alpha \) are the shape parameters and 
- \( P_0 \) is the reference capillary pressure.

Equation (9) defines the relationship between the mobility coefficient utilized in FLAC \( K \), which characterizes permeability, and the hydraulic conductivity commonly employed in expressing Darcy's \( K_s \) law in terms of head.

\[
K = \frac{K_s}{(g \rho_w)} 
\]  

2.2 SLOPE MODEL AND INITIAL CONDITIONS

The first objective of this investigation is to analyze the process of infiltration in various unsaturated soil layers, as shown in (Figure 2). Based on site observations, it has been noted that certain slopes exhibit a layer between 0 and 4 meters in depth. This layer consists of a mixture of clay and sandstone (soil 2) and is situated at a higher elevation. Consequently, a study was initiated to investigate
the impact of both the hydrological and mechanical properties of this layer, as well as its thickness, on slope stability. The study encompasses five distinct scenarios:

- case 1: A single layer of soil composed of clay loams (H = 0);
- case 2: The effects of multiple layers are explored, with the top layer consisting of a H = 1-meter thickness of clay and sandstone;
- case 3: H = 2-meter thickness of clay and sandstone;
- case 4: H = 3-meter thickness of clay and sandstone;
- case 5: H = 4-meter thickness of clay and sandstone.

Rainfall was applied at the ground surface (ABCD) as a boundary condition. A displacement into the parallel direction was fixed at the left and right sides (AF and DE), and the bottom surface (FE) was fully constrained.

To ensure the model effectively captures essential aspects of slope geometry and boundary conditions, a sensitivity analysis of the model dimensions is conducted to avoid unrealistic results. Adjustments are made to the dimensions to maintain accuracy while speeding up the simulation process. The decision to use a 2D model is driven by the need to conserve computational resources, such as memory and processing time, while still gaining valuable insights into slope stability. Many slope stability problems manifest predominantly in two-dimensional failure mechanisms, making a 2D analysis sufficient to capture these mechanisms without the added complexity of a three-dimensional model.
In the upcoming stage of the study, the influence of slope height (8m, 10m, 12m) will be assessed while focusing on a single layer of soil, namely clay loam. Maintaining a constant slope angle, variations will be introduced in both the initial saturations and the initial pore water pressures, as they are interconnected. The effect of rainfall infiltration on slope stability will be evaluated by applying different precipitation with a duration corresponding to five days. A comparative analysis between FLAC and PLAXIS software will then be conducted to explore how the hydrological and mechanical properties of soils impact slope stability. A slope angle of approximately 34 degrees, as shown in (Figure 2), will be used for all the analyses.

2.3 SOIL PROPERTIES

Field and laboratory tests, including direct shear tests and soil-water characteristic curve (SWCC) analyses, were conducted to obtain the necessary material properties of the soil. These tests are crucial for accurately simulating slope behavior and analyzing the infiltration process. The filter paper method was used to measure volumetric water content, which depends on matric suction under wetting conditions. The SWCC function in this study is based on the Van Genuchten (1980) model, providing an accurate description of the soil's hydraulic properties. When constructing the model, layer inputs were specifically tailored to the soil slope being simulated, as detailed in Table 1 and Figure 2. Table 1 outlines the properties of three soils: Soil 1 (clay loams), Soil 2 (clay and sandstone), and Soil 3 (silty clay). Soil 1 has a dry density of 18 kN/m³, bulk modulus of 9.8 × 10⁶ Pa, shear modulus of 3.76 × 10⁶ Pa, cohesion of 12 kPa, friction angle of 21 degrees, and hydraulic conductivity of 1.81 × 10⁻⁶ m/sec. Soil 2 has a dry density of 17.5 kN/m³, bulk modulus of 6.67 × 10⁶ Pa, shear modulus of 3.07 × 10⁶ Pa, cohesion of 15 kPa, friction angle of 19 degrees, and hydraulic conductivity of 3.94 × 10⁻⁶ m/sec. Soil 3 shows a dry density of 20 kN/m³, bulk modulus of 2.33 × 10⁷ Pa, shear modulus of 5 × 10⁶ Pa, cohesion of 31 kPa, friction angle of 13.5 degrees, and hydraulic conductivity of 1.42 × 10⁻⁶ m/sec. The shape parameters (m and α) and reference capillary pressures (P₀) differ among the soils, with Soil 1 showing m = 0.5306, α = 0.247, and P₀ = 39.77 kPa, Soil 2 showing m = 0.5302, α = 0.067, and P₀ = 146.42 kPa, and Soil 3 showing m = 0.547, α = 0.09, and P₀ = 108.95 kPa. Figure 2 presents the SWCCs used in this study, demonstrating how these properties impact the soil's response to matric suction and informing the model's construction and analysis of infiltration behavior.
Table 1. Properties of soil, water, and air.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Soil 1</th>
<th>Soil 2</th>
<th>Soil 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry density, $\gamma_d$ (kN/m³)</td>
<td>18.00</td>
<td>17.50</td>
<td>20.00</td>
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<tr>
<td>Bulk modulus, $K$ (kPa)</td>
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<td>$6.66 \times 10^3$</td>
<td>$2.32 \times 10^4$</td>
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<tr>
<td>Shear modulus, $G$ (kPa)</td>
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<td>$3.06 \times 10^3$</td>
<td>$5.1 \times 10^3$</td>
</tr>
<tr>
<td>Cohesion, $C$ (kPa)</td>
<td>12</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>Friction angle, $\Phi$</td>
<td>21</td>
<td>19</td>
<td>13.5</td>
</tr>
<tr>
<td>Hydraulic conductivity, $K_s$ (m/sec)</td>
<td>$1.80 \times 10^{-6}$</td>
<td>$3.93 \times 10^{-6}$</td>
<td>$1.41 \times 10^{-6}$</td>
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<td>Viscosity ratio, $\mu_w/\mu_a$</td>
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<td>55</td>
<td>55</td>
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<td>Air density, $\rho_a$ (kg/m³)</td>
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<td>1.25</td>
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<tr>
<td>Water density, $\rho_w$ (kg/m³)</td>
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<td>Bulk modulus of air, $K_a$ (kPa)</td>
<td>$1 \times 10^2$</td>
<td>$1 \times 10^2$</td>
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<td>Bulk modulus of water, $K_w$ (kPa)</td>
<td>$1 \times 10^6$</td>
<td>$1 \times 10^6$</td>
<td>$1 \times 10^6$</td>
</tr>
<tr>
<td>Shape parameter, $\alpha$</td>
<td>0.247</td>
<td>0.067</td>
<td>0.09</td>
</tr>
<tr>
<td>Shape parameter, $m$ (Vga in flac)</td>
<td>0.5305</td>
<td>0.5301</td>
<td>0.548</td>
</tr>
<tr>
<td>Reference capillary pressure, $P_0$ (kPa)</td>
<td>39.78</td>
<td>146.41</td>
<td>108.94</td>
</tr>
</tbody>
</table>

Source: Prepared by the authors

3 RESULTS AND DISCUSSIONS

3.1 EFFECTS OF SOIL LAYERS ON SLOPE STABILITY UNDER RAINFALL INFILTRATION

To investigate the effects of different soil layer configurations on slope stability under rainfall infiltration, a consistent rainfall intensity was maintained across all scenarios. The results are depicted in (Figure 4), which highlights the vertical profile of matric suction and the corresponding safety factors under varying conditions.

Figure 4 illustrates how different soil layer configurations affect slope stability under varying rainfall intensities. Under steady-state conditions (Figure 4a), the scenario with $H=0$ m displays a uniform distribution of matric suction, indicative of a homogeneous soil profile. When the soil profile includes a
1 m layer of clay and sandstone (H=1 m), there is an increase in suction beneath this layer, which enhances moisture retention and slope stability. As the thickness of the clay and sandstone layers increases (H=2, 3, and 4 m), water infiltration is further impeded, leading to even higher suction and consequently greater slope stability.

Figure 4. Vertical profile of matric suction in various layer cases: (a) at the steady state condition 0mm/h; (b) with an intensity IR of 5mm/h; (c) with an intensity IR of 10 mm/h; (d) Variation of the safety factor at different rainfall intensities over five-day period.
Under rainfall intensities of 5 mm/h and 10 mm/h (Figures 4b and 4c), matric suction decreases across all cases. However, the case with a 4 m layer of clay and sandstone (H=4 m) retains the highest level of suction at depth, followed by other cases. This indicates a more robust moisture retention capability, contributing to enhanced stability under higher rainfall intensities.

Figure 4d shows the variation in the safety factor with increased rainfall intensity over five days. The safety factor decreases for all cases as rainfall intensity increases, with the most significant reduction observed in the H=0 m scenario, indicating higher susceptibility to instability. In contrast, the configurations with H=2 and H=3 m show a moderate decrease in the safety factor. The scenario with H=4 m maintains the highest safety factor due to its effective suction profile, thus demonstrating the most resilience against slope instability under intense rainfall conditions.

3.2 EFFECTS OF THE SLOPE HEIGHT AND THE INITIAL SATURATION

To analyze the influence of slope height on stability during rainfall, simulations were conducted for slopes with heights of 8, 10, and 12 meters. The results, shown in (Figure 6), indicate that slopes with lower heights exhibit greater stability in terms of the factor of safety (FoS). This increased stability is due to the more favorable distribution of soil stress within shorter slopes. However, the rate at which the FoS decreases due to rainfall is more pronounced for shorter slopes.

Figure 6(a) shows the variation of the safety factor over five days with different rainfall intensities. For an 8-meter slope, the FoS decreases by 0.26 under 10 mm/h rainfall, while for a 12-meter slope, the
decrease is 0.17. This indicates that although shorter slopes are initially more stable, they are more sensitive to rainfall, experiencing a steeper decline in stability.

Figure 6. Variation of the safety factor in various slope heights: (a) at different rainfall intensities over 5-day period; (b) at various initial saturation with IR of 10 mm/h.

Figure 6(b) examines the impact of initial soil saturation on the safety factor with a consistent rainfall intensity of 10 mm/h. The decrease in the FoS is again more substantial for the 8-meter slope, highlighting that initial saturation significantly affects slope stability. Slopes with lower heights, regardless of initial saturation levels, exhibit a more pronounced reduction in stability under rainfall. This is attributed to the failure surface being closer to the slope’s surface, making it more susceptible to rainfall infiltration.

3.3 COMPARISON IN FINITE ELEMENT AND FINITE DIFFERENCE METHODS

3.3.1 Suction profile comparison

Evaluating the safety factor in unsaturated slopes necessitates an analysis of the suction profile, which reflects hydrostatic conditions following rainfall infiltration. For this part of the study, three different soil types were analyzed, as depicted in (Figure 7), each subjected to a 10 mm/h rainfall intensity over five days. The initial suction values, set at 50% of initial saturation, were carefully considered to ensure the comparison's validity, with multiple simulation tests cross-verified against previous studies.

The initial suction values play a crucial role in seepage analysis. The first soil type showed a steady-state suction of 62.5 kPa at 50% saturation. In contrast, the second soil type exhibited 200 kPa, and the third had a suction level of 141 kPa. Figure 7 illustrates these distinctive profiles, demonstrating the progressive seepage phenomena due to rainfall infiltration. After five days of
continuous rainfall, significant differences in the suction profiles were noted between PLAXIS FEM and FLAC FDM simulations.

While both software tools produced nearly identical pressure values at 1 meter and 10 meters below the surface, notable discrepancies emerged in the 2 to 9-meter depth range. These variations can be attributed to the differing permeability equations employed by the two software platforms.

![Figure 7. Vertical distribution of matric suction across different soil types.](image)

3.3.2 Safety factor comparison

To evaluate the results from PLAXIS and FLAC, the models were configured according to their properties and subjected to different rainfall intensities, as summarized in (Figure 9). The Figure highlights the distinctions between the Factors of Safety (FOS) calculated by both programs.

The effect of rainfall intensity on the safety factor is illustrated in the graphs. The figures demonstrate how the FOS changes with increasing rainfall intensity for three different soil types. The FOS values derived from FLAC are generally lower than those from PLAXIS in 80% of the scenarios. Additionally, the decrease in FOS with rainfall intensity from 0 to 10 mm/h is more significant in the PLAXIS results compared to those from FLAC.

For Soil 1, both PLAXIS and FLAC show a decline in FOS with increasing rainfall intensity, but the reduction is more pronounced in the PLAXIS results. Similarly, for Soil 2 and Soil 3, PLAXIS consistently produces higher FOS values than FLAC, with the difference becoming more noticeable as rainfall intensity increases. This indicates that PLAXIS may be more sensitive to changes in rainfall intensity compared to FLAC.
The differences in factor of safety (FOS) calculations among the soils are primarily due to the variations in their initial suction levels. Soil 2, with a high initial suction of 200 kPa, exhibits significant discrepancies in FOS results across different computational programs, which can be attributed to the complex and non-linear relationship between suction and shear strength. This complexity necessitates
distinct modeling approaches, leading to variability in outcomes. Conversely, Soil 1, with a lower initial suction of 62.5 kPa, shows more consistent FOS values between programs. The simpler and more linear relationship between suction and shear strength in this range reduces the impact of modeling differences. Overall, higher initial suction introduces greater complexity and variability in FOS calculations, while lower suction results in more consistent and convergent FOS values due to the reduced influence on shear strength. Despite these variations, the average difference in FOS values between the two programs is less than one percent, reflecting a generally close agreement that is influenced by the differences in permeability equations and numerical methods used by the software.

4 CONCLUSION

This study underscores the significant impact of soil layering, specifically in a slope within the Tebessa region, highlighting the presence and thickness of clay and sandstone layers and their influence on slope stability during rainfall events. Thicker layers of less permeable materials, such as those in Case 5, maintain higher matric suction and safety factors despite increased rainfall, emphasizing the critical role of soil layering in managing slope stability and mitigating risks from rainfall infiltration. Furthermore, the research reveals that lower slopes initially offer greater stability but are more susceptible to rainfall-induced instability due to their proximity to the failure surface. The study also emphasizes the importance of initial soil saturation, with higher saturation leading to lower safety factors. Regarding numerical modeling, PLAXIS tends to predict higher safety factors than FLAC, highlighting the need for appropriate modeling approaches in accurate slope stabilization assessments. Additionally, higher initial suction introduces greater complexity and variability in FOS calculations between software packages. Overall, the study underscores the necessity of integrating detailed hydromechanical analyses, accurate rainfall data, and considerations of slope geometry and soil layering for effective slope stability assessment and development of robust stabilization measures, thereby enhancing safety and resilience in landslide-prone regions.
REFERENCES


