A comparative study of critical failure surface in unsaturated soil slopes.

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Abstract. Landslides are rapid downslope movements triggered by factors such as rainfall, earthquakes, or human activity, where factors like relative permeability, air flow, and variations in hydraulic conductivity affect the mechanisms behind rainfall infiltration and landslide occurrence. This study investigates these phenomena using the finite difference method (FDM) and finite element method (FEM) in FLAC and PLAXIS software. These methods account for the coexistence of water and air, including the Two-phase flow option, in evaluating unsaturated slope stability and identifying critical failure surfaces. The efficiency of these approaches is gauged by varying soil parameters and exploring the impact of different values of suction and hydraulic conductivity, as well as soil-water characteristics, on the safety factor. It was observed that there are disparities between both software packages at high suction values, which impact the safety factor. FLAC is noted for its conservative approach and superiority in representing unfavourable conditions.

1 Introduction

Predicting the risk of landslides due to rainfall is crucial, especially in mountainous regions and steep areas. These landslides occur when the soil loses its cohesion and moves downhill, posing a threat to infrastructure and human lives. Various factors contribute to increased landslide risks, including soil characteristics, geological relief, precipitation intensity, terrain slope, and human activities, where the slope failures triggered by rainfall have frequently been reported worldwide.

There are two primary techniques for evaluating how unsaturated soils react to rainfall infiltration: the coupled and uncoupled methods. In the uncoupled approach, the first step involves conducting seepage analysis to predict pore water pressures. These pressures are then utilized as data for deformation or stability analysis. On the other hand, the coupled approach takes into account the mutual influence between seepage and deformation by simultaneously solving for pore water pressures and deformation during rainfall infiltration. This integrated approach provides a more realistic representation of the physical interaction between water flow and stress-strain changes within unsaturated soils.

Previous research has made substantial contributions to the field of unsaturated slope stability analysis. These studies have revealed that the coupled hydro-mechanical model (CHM) yields the most accurate results when simulating rainfall infiltration [10], Additionally, these investigations have delved into the correlation between slope stability and rainfall intensity and duration. The earlier findings have underscored that analysing slope stability in an unsaturated state is a more practical approach, as it accounts for the actual groundwater level (GWL) position and the alterations in shear strength due to deformation and fluctuations in pore-water pressure [5].

With advancements in technology, the utilization of software packages employing finite difference and finite element methods has gained significant popularity. Currently, slope stability poses a prominent challenge for soil professionals and engineers, with ongoing debate among scientists regarding the most effective approach for slope stability assessment.

This study's primary objectives encompass the utilization of various slope stability analysis software tools to assess the influence of site-specific hydrological characteristics, specifically the Soil-Water Characteristic Curve (SWCC) and the rainfall intensity, on the safety and the determination of critical slip surfaces. Furthermore, this research aims to compare the outcomes derived from different slope stability analysis software programs. To achieve these goals, three distinct soil types were obtained from the Tebessa region, each characterized by unique hydrological parameters, are simulated and analysed within this study.

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2 Model formulation

2.1 Slope stability analysis by finite elements and finite difference

The finite element analysis (FEA) and finite difference (FDM) locates the critical failure surface based on a calculation of failure shear strain zones which have been shown to coincide with rupture surfaces in experimental tests. The method of calculation of FoS in PLAXIS 2D and FLAC 2D is the shear strength reduction method.

When analysing unsaturated slopes in FLAC, suction is typically incorporated through constitutive models such as the Soil Water Characteristic Curve (SWCC) and the unsaturated soil shear strength parameters. The impact of suction on the safety factor of unsaturated slopes in FLAC is influenced by the explicit representation of soil-water-air interactions, allowing for a detailed analysis of moisture-induced changes in soil behaviour and its effect on slope stability. On the other hand, PLAXIS utilizes a finite element method (FEM) for numerical analysis, focusing on the discretization of the soil domain into finite elements. PLAXIS offers various constitutive models to account for unsaturated soil behaviour, including the Van Genuchten model for the soil-water retention curve. In PLAXIS, suction influences the safety factor of unsaturated slopes by affecting soil shear strength parameters and pore-water pressure distributions.

To numerically model the initiation of slope failures caused by rainfall under unsaturated conditions, it is necessary to develop a hydromechanically coupled transient analysis in a systematic way. In the case of unsaturated soil, the pore volume is partially filled with water, while the remaining portion is occupied by air. Consequently, the key disparity between the shear strength of saturated and unsaturated soils lies in the definition of effective normal stress.

A practical Equation (1) provided by Bishop is used in PLAXIS and FLAC to define the shear strength of unsaturated soil. This equation incorporates parameters like the frictional resistance angle (φ), pore air pressure (P_a), and pore water pressure (P_w), and it is expressed as:

$$\tau_{\max} = (\sigma - P_a)\tan\varphi' + (P_a - P_w)\tan\varphi' + c' \qquad (1)$$

the safety factor is obtained as:

$$F_s = \frac{\tau_{\max}}{\tau_n} \qquad (2)$$

Where (τ_n) is the reduced shear strength that is just large enough to maintain equilibrium.

2.2 Unsaturated flow

Matric suction is described as the difference between pore air pressure and pore-water pressure. The connection between soil water content and pore-water pressure is represented as the soil-water characteristic curve (SWCC), which plots volumetric moisture content against matric suction.

A commonly employed approach to represent the hydraulic properties of unsaturated soils is the set of closed-form equations introduced by van Genuchten. These equations are built upon Mualem's capillary model. The capillary pressure law used in FLAC is in the following van Genuchten form:

$$P_c = P_0\left[\left(S_e\right)^{-\frac{1}{m}} - 1\right]^{1-m} \qquad (3)$$

$$P_0 = \frac{\rho_w g}{\alpha} \qquad (4)$$

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

Equation (5) defines the relationship between the mobility coefficient utilized in FLAC, which characterizes permeability, and the hydraulic conductivity commonly employed in expressing Darcy's law in terms of head.

$$K = \frac{K_s}{(g\rho_w)} \qquad (5)$$

2.3 Slope Parameters

The primary aim of this comparative study is to assess soil infiltration processes using FLAC and PLAXIS software while exploring how the hydrological and mechanical properties of soils impact the slope stability and length of the arc of failure. The slope angle of approximately 34 degrees was selected, as shown (see Fig. 1). which was considered for the analysis.

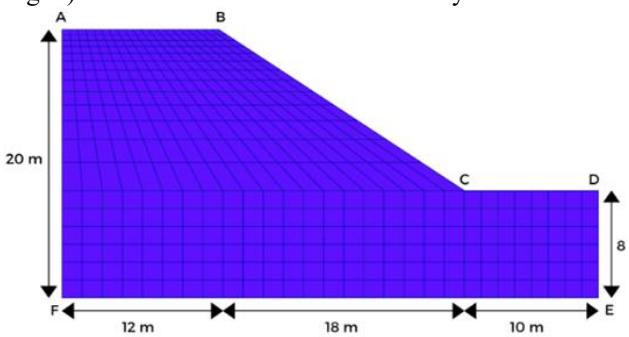

Fig .1. Slope geometry and boundary conditions adopted in this study.

Field and laboratory tests, direct shear tests, and soil-water characteristic curve (SWCC), were conducted to obtain the necessary material properties of the soil. These tests provide crucial data for accurately simulating the behaviour of the slope and analysing the infiltration process. When constructing the model, the layer inputs were tailored to the specific properties of the soil slope being simulated. A detailed description of these inputs can be found in the provided (see Fig. 2 and Table.1).

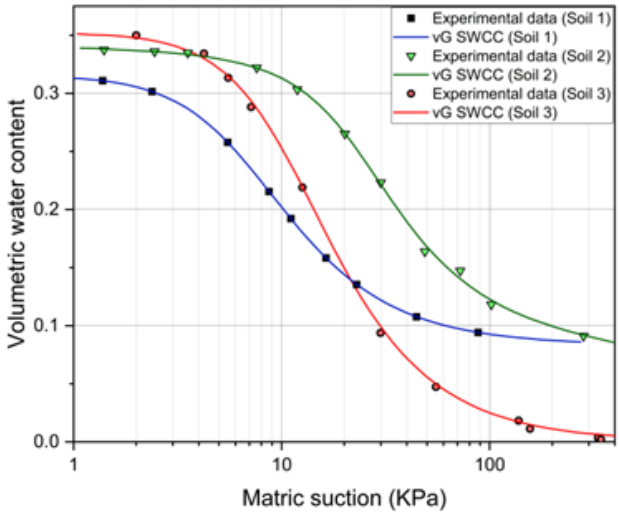

Fig .2. SWCCs used in this study.

Table 1. Properties of soil water, and air.

Parameter	Soil 1	Soil 2	Soil 3
Dry density ***γd*** (kN/m3)	18	17.5	20
Bulk modulus ***K*** (kPa)	9.8×10^3	6.67×10^3	2.33×10^4
Shear modulus ***G*** (kPa)	3.76×10^3	3.07×10^3	5×10^3
Cohesion ***C*** (kPa)	12	15	31
Friction angle ***Φ***	21	19	13.5
Hydraulic conductivity ***Ks*** (m/sec)	1.81×10^{-6}	3.94×10^{-6}	1.42×10^{-6}
Shape parameter ***α***	0.247	0.067	0.09
Shape parameter ***m***	0.5306	0.5302	0.547
Reference capillary pressure ***P0*** (kPa)	39.77	146.42	108.95

3 Results and discussion

3.1 Comparison of suction profile

When assessing the factor of safety in unsaturated slopes, it's crucial to examine the suction profile, which represents hydrostatic conditions after rainfall infiltration. Consequently, a predictive study was performed for each soil type as shown in (Figure 3), subjecting them to a 10 mm/h rainfall intensity over a 5-day duration. It's noteworthy that the comparison was conducted rigorously, considering the initial suction values, which were set at 50% of initial saturation in all cases. Multiple simulation tests were carried out to confirm the accuracy of the approach using previous studies [4].

In the context of seepage analysis, the initial suction values for distinct soil types hold considerable significance. The first soil type is characterized by a steady-state suction of -69 kPa at 50 % of initial saturation, whereas the second type exhibits a significantly lower value of -200 kPa, and the third soil type is associated with a suction level of -141 kPa. These distinctive suction profiles, as showcased in Figure 3, provide a clear illustration of the progressive seepage phenomena resulting from the infiltration of rainfall.

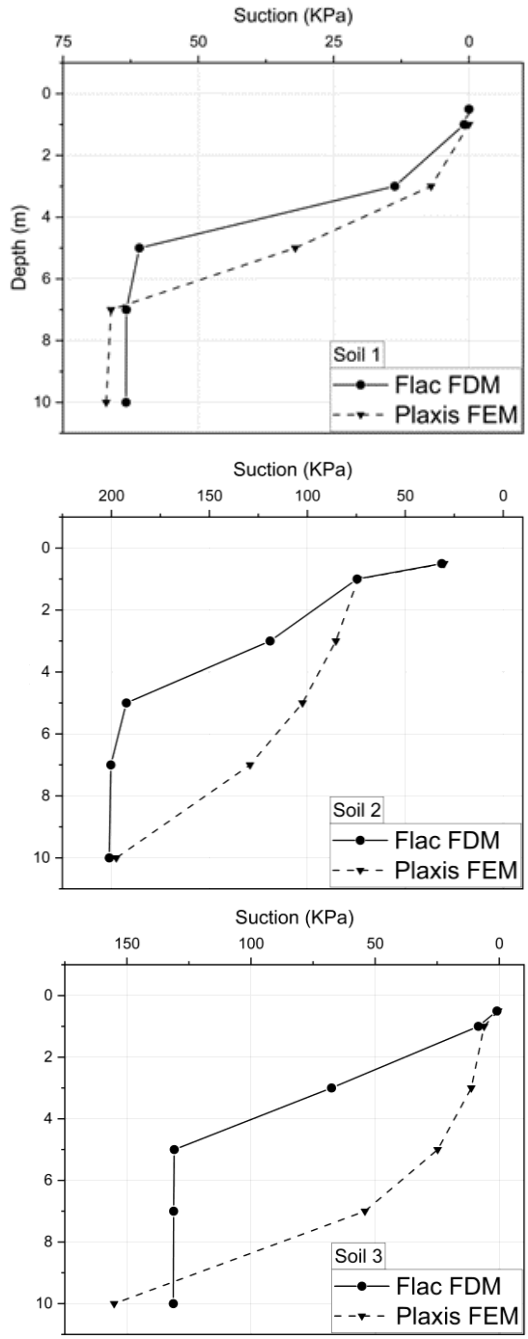

Fig .3. Vertical profile of matric suction in various soil type.

Following five days of continuous rainfall, a notable disparity emerges in the behaviour of the PLAXIS 2D pore pressure profile when compared to the FLAC software. It is worth noting that both software programs yield nearly identical pressure values at depths of 1 meter below the surface and 10 meters, but intriguingly, the disparities in pressure values become most apparent within the depth range of 2 to 9 meters. This discrepancy can be attributed to variations in the permeability equations employed by the two software platforms.

In general, the use of higher-nodded elements, whether in triangular, quadrilateral, or mixed configurations, offers a more robust and accurate solution due to the increased number of integrations

points during the numerical integration process in finite element seepage analysis.

3.2 Safety factor comparison

To inspect the outputs from PLAXIS and FLAC the models were chosen up to their properties and exposed to various rainfall intensities as shown in Tables 2 which summarizes the distinction between the FOS acquired from both programs and compares these results using the following formula:

$$Difference = \frac{\mathrm{FOS(FLAC)} - \mathrm{FOS(PLAXIS)}}{\frac{\mathrm{FOS(FLAC)} + \mathrm{FOS(PLAXIS)}}{2}} \times 100$$

Table 2. The difference of FOS between FLAC and PLAXIS.

Soil Type	Rain Intensity (mm/h)	FLAC FOS	PLAXIS FOS	Difference %
1	0	1.64	1.662	-1.33
	2.5	1.611	1.637	-1.6
	5	1.576	1.534	-2.7
	7.5	1.533	1.274	18.45
	10	1.463	1.175	21.8
2	0	2.225	3.25	-37.44
	2.5	2.209	3.196	-36.52
	5	2.186	3.973	-30.5
	7.5	2.158	2.782	-25.26
	10	2.127	2.415	-12.68
3	0	1.762	1.926	-8.89
	2.5	1.74	1.901	-8.84
	5	1.725	1.862	-7.63
	7.5	1.706	1.761	-3.17
	10	1.678	1.663	0.89

The influence of rainfall intensity and hydrologic characteristics on the safety factor is visually represented in the table. Notably, there is a significant difference in FOS values between the FLAC and PLAXIS programs in certain cases. For the first type of soil, under steady-state conditions and with rainfall intensity less than 5 mm, there was no difference.

However, it is important to note that the greater the initial suction, the larger the difference in the safety factor. As rainfall rate increased, the disparity also increased. It is noticeable that FOS values obtained from FLAC are lower in 80% of the scenarios, and the rate of decrease in FOS from 0 to 10 mm/h in PLAXIS is greater than in FLAC.

3.3 Impact of rainfall intensity on the slip surface length

In this study, the impact of rainfall intensity on the slip surface was carefully examined, with a particular focus on the length of the failure arc (La) as a quantitative variable. To accurately assess this, precise measurements were obtained by creating circles using AutoCAD software to identify entry and exit points within the slope area, allowing for a comprehensive analysis of the failure arc.

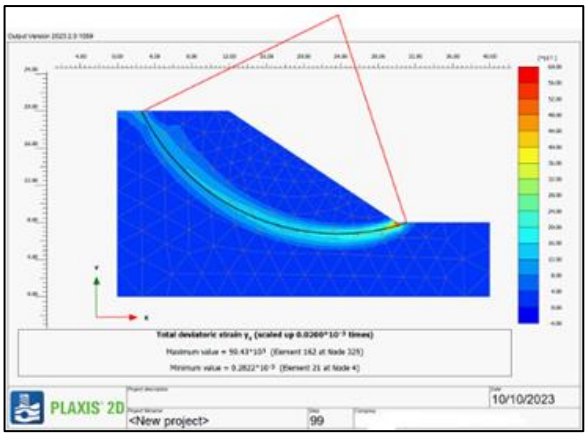

Fig .4. Failure arc creation in AutoCAD

Inclusion of Figures (5) in this study offer a comprehensive visual depiction of the research findings. These figures elucidate the relationship between hydrological characteristics and rainfall intensity, shedding light on their collective impact on the variation in the length of the failure arc within the unsaturated slope systems under investigation. Through meticulous analysis, it becomes evident that heightened rainfall intensity correlates directly with a discernible reduction in the length of the surface failure arc.

Moreover, an observation arises from the comparative analysis of the results obtained from FLAC and PLAXIS. Despite FLAC exhibiting lower safety factor values, it is intriguing to note that the length of the failure surface in FLAC surpasses that in PLAXIS. This observation unveils a compelling insight into the nuanced interplay between numerical modelling methodologies and the resulting surface failure characteristics.

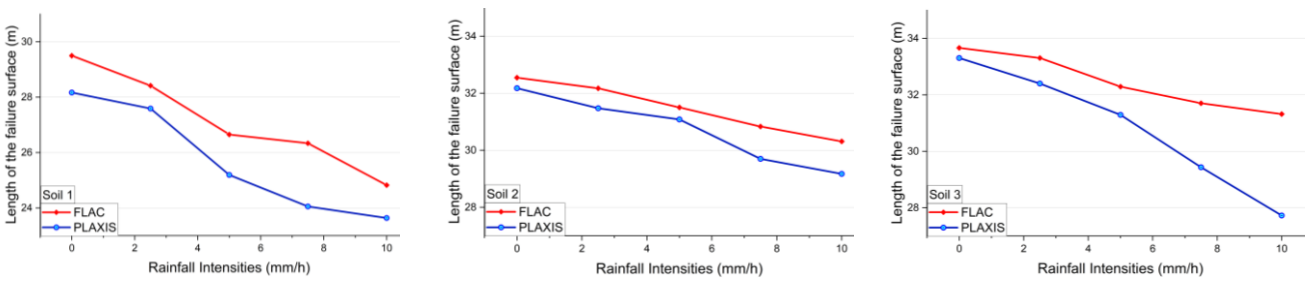

Fig .5. The effect of IR on La in different types of soils.

It suggests that the choice of software platform can exert a discernible impact on the morphology of failure surfaces within unsaturated slope systems. Such observations prompt a deeper exploration into the underlying mechanisms driving these variations, necessitating further investigation and analysis to elucidate the factors influencing the discrepancy between FLAC and PLAXIS results in terms of failure surface length. This insight underscores the importance of meticulous consideration when selecting a numerical modelling approach, as it can profoundly shape the outcomes and interpretations derived from slope stability analyses.

4 Conclusions

This comparative review of popular computer programs for rainfall-induced seepage unsaturated slope problems highlights the direct relationship between hydrological characteristics, rainfall intensities, and safety factors. Notably, in fully coupled numerical models using FLAC and PLAXIS 2D, hydraulic conductivity (ks) emerges as the primary controlling parameter for the hydromechanical response and failure time of unsaturated slopes subjected to rainfall infiltration.

Despite FLAC's inherent complexities, it emerges as the more conservative software for slope stability studies compared to PLAXIS, because usually gave out the lowest value for factor of safety in comparison. Furthermore, an increase in rainfall intensity results in a reduced length of the failure arc (La) and factor of safety (FOS), with FLAC showing the longest failure length compared to PLAXIS. This characteristic makes FLAC a suitable choice for engineers, as it represents the most unfavorable conditions. Further studies and modification to the DLL file in the PLAXIS program are needed to simulate the infiltration process.

References

1. PLAXIS 1D/2D/3D Saturated/Unsaturated Finite Element Groundwater Modeling (Theory Manual). (2023)
2. A.S. Chatra, G. R. Dodagoudar, V. B. Maji, Numerical modelling of rainfall effects on the stability of soil slopes, International Journal of Geotechnical Engineering. **13**, 425-437 (2019) https://doi.org/10.1080/19386362.2017.1359912
3. F. Cai, K. Ugai, Numerical analysis of rainfall effects on slope stability. International Journal of Geomechanics. **4**, 69–78 (2004) https://doi.org/10.1061/(ASCE)1532-3641(2004)4:2(69)
4. J.W. Mburu, A-J. Li, H-D. Lin, C-W. Lu, Investigations of Unsaturated Slopes Subjected to Rainfall Infiltration Using Numerical Approaches—A Parametric Study and Comparative Review. Sustainability. **14**, 14465 (2022) https://doi.org/10.3390/su142114465
5. H-E. Chen, T-L, Tsai, J-C, Yang, Threshold of Slope Instability Induced by Rainfall and Lateral Flow. Water. **9**, 722 (2017) https://doi.org/10.3390/w9090722
6. D.G. Fredlund, N.R. Morgenstern, R.A. Widger, The shear strength of unsaturated soils. Canadian Geotechnical Journal. **15**, 313–321 (1978) https://doi.org/10.1139/t78-029
7. S.L. Barbour, D.G. Fredlund, M.D. Fredlund, A. Xing, The relationship of the unsaturated soil shear strength to the soil-water characteristic curve. Canadian Geotechnical Journal. **33**, 440–448 (1995) https://doi.org/10.1139/t96-065
8. S.G. Goh, E.C. Leong, H.Rahardjo, Shear Strength Equations for Unsaturated Soil under Drying and Wetting. Journal of Geotechnical and Geo-environmental Engineering. **136**, 594-606 (2010) https://doi.org/10.1061/(ASCE)GT.1943-5606.0000261
9. Itasca Manual. Fluid–Mechanical Interaction, FLAC 8.0, Itasca Consulting Group, Inc (2011)
10. S.U. Cho, S.Kang, S.T. Lee, Slope stability analysis of unsaturated soil slopes based on the site-specific characteristics: a case study of hwangryeong mountain, Busan, Korea. Sustainability. **12**(7), 2839 (2020) https://doi.org/10.3390/su12072839
11. K. Terzaghi, Mechanism of Landslides, The Geological Society of America. **Berkey volume**, 83–123 (1950)
12. M.T. Van Genuchten, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. soil science society of America journal. **44**, 892–898 (1980) https://doi.org/10.2136/sssaj1980.03615995004400050002x