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IMPACT OF SWCC MEASUREMENT METHODS ON THE NUMERICAL INVESTIGATIONS OF UNSATURATED SOILS

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ABSTRACT
The soil-water characteristic curve SWCC, also known as the soil-water retention curve SWRC, describes the relationship between soil suction and water content in unsaturated soils. Many studies rely on specific laboratory testing methods without considering their impact on numerical simulations. This research investigates the effect of different SWCC measurement techniques on numerical modeling outcomes. Soil samples from the Tebessa region were tested using three methods: the filter paper method, the osmotic technique, and the axis translation technique. Numerical simulations were then conducted using FLAC software to analyze the influence of these methods on the hydromechanical properties of unsaturated soils and slope stability under two days of wetting conditions. The results indicate that the selected SWCC measurement method significantly affects the predicted vertical suction profile and influence the factor of safety (FOS) in slope stability analysis. This suggests that while accurate suction measurements are crucial for understanding soil behavior, their overall impact on slope stability predictions varies depending on the testing technique employed.
Keywords: *Soil-Water Characteristic Curve, Unsaturated Soils, Infiltration, Landslide, FLAC 2D.*

1. Introduction

The mechanical and hydraulic behavior of soils is fundamentally governed by their saturation state. Classical soil mechanics provides a well-established framework for saturated soils, where the pore space is entirely filled with water. In contrast, unsaturated soil mechanics addresses the more complex three-phase system (solid, water, air), where the presence of matric suction induces highly nonlinear behavior. The analysis of critical geotechnical problems, such as slope stability, foundation heave, and seepage, in unsaturated zones requires the use of constitutive property functions to solve the governing nonlinear partial differential equations (Fredlund, 2017).

The pivotal element for estimating these unsaturated soil property functions is the Soil-Water Characteristic Curve (SWCC), which describes the relationship between soil suction and water content. The SWCC serves as the primary tool for predicting hydraulic conductivity and water storage capacity, which are essential for modeling transient flow (Carvalho et al., 2015; Liu et al.,2024), making it fundamental in geotechnical and geo-environmental engineering. Consequently, the accurate determination of the SWCC is a prerequisite for reliable numerical simulations (Fredlund & Rahardjo, 1993)

Multiple standardized laboratory techniques exist for measuring the SWCC, it can be measured directly or indirectly. Indirect methods, such as gypsum blocks, thermocouple psychrometers, and soil moisture sensors (TDR or FDR), require calibration to relate sensor readings to suction values. However, these approaches are generally less accurate than direct methods because the measured properties do not perfectly represent suction (Bello et al., 2025). However, significant evidence indicates that the choice of methodology influences the resulting curve (Zhai et al., 2023). Nam et al. (2010) showed that different methods cover distinct suction ranges, with pressure plate and Tempe cell techniques reliable up to ~1500 kPa, while filter paper methods are slower and more error-prone. These differences lead to variations in key parameters such as the air-entry value and residual water content. Furthermore, factors such as stress conditions significantly influence results; Habasimbi et al. (2018) demonstrated that isotropic confinement densifies soil structure and increases water retention, while one-dimensional confinement yields different results. Discrepancies between experimental and predictive SWCC further highlight this variability, as they depend strongly on the measurement method for input parameters like grain-size distribution (Marcos et al., 2020). This methodological discrepancy presents a critical, yet often unquantified, source of uncertainty.

This problem is exacerbated when SWCC parameters are used as inputs for numerical models predicting hydro-mechanical behavior, such as slope stability under rainfall infiltration. Rainfall infiltration leads to a reduction in soil suction, which decreases shear strength and pore water pressure, ultimately contributing to slope instability (Liu et al., 2015; Wu et al., 2025). Sophisticated Coupled Hydromechanical Models (CHM) have shown that the evolution of pore-water pressure and the computed factor of safety are highly sensitive to the underlying hydraulic properties defined by the SWCC (Angelaki et al., 2023). For instance, Kang et al. (2021) found that models incorporating two-phase flow (water and air) provide more realistic predictions than single-phase models, capturing a rapid decrease in safety factors during weak rainfall. The hydraulic properties of near-surface soils, including the SWCC, play a critical role in governing this infiltration behavior and slope stability (Zhang et al., 2014). Therefore, variability in the SWCC input must propagate directly into uncertainty in the model's predictions of performance and stability. While extensive research has focused on developing numerical models and studying slope geometry, the specific impact of the SWCC measurement technique on the outcome of these simulations remains inadequately investigated. As highlighted by comparisons between in-situ monitoring and laboratory tests, systematic differences exist, yet their direct impact on modeling outcomes is not well quantified. There is a clear gap in understanding how the choice of laboratory method influences the accuracy and reliability of numerical predictions.

This study aims to address this gap by systematically evaluating the impact of different SWCC measurement techniques on numerical slope stability analysis for a soil from the Tebessa region. Three common laboratory methods: the axis-translation, osmotic, and filter paper techniques, were applied and compared. The resulting parameters were integrated into the modified van Genuchten-Mualem (mvG-M) model within the FLAC software environment to simulate infiltration under a uniform rainfall event. FISH scripts were employed to simulate infiltration rates and hydro-mechanical interactions under a uniform rainfall of 5 mm/h.

The simulations revealed significant variations in soil saturation predictions, suction distribution, and safety factor evolution. The results highlight the critical importance of initial soil saturation in failure mechanisms while providing a comparative assessment of the reliability of different SWCC measurement techniques for slope stability analysis.

2. Literature Review

Suction is a crucial parameter in soil mechanics, yet its accurate measurement remains challenging due to its broad range in unsaturated soils. Various methods have been developed to measure and control suction, including direct and indirect techniques. (Nam et al., 2010) conducted a study comparing testing techniques and models for establishing the SWCC of riverbank soils. The research evaluates six laboratory methods (filter paper, dewpoint potentiometer, vapor equilibrium, pressure plate, Tempe cell, and osmotic technique) using soil samples from the Lower Roanoke River in North Carolina. Additionally, three empirical models (van Genuchten, (1980); Fredlund and Xing, (1994); and Houston et al., (2006)) were assessed for their effectiveness in fitting the experimental data. The findings indicate that while each testing method covers different suction ranges, their combined results yield continuous SWCC. The empirical models were found to be suitable for matric suction values below 1500 kPa. The study highlights the variability in SWCC results due to methodological differences, stressing the importance of selecting appropriate testing techniques and models for accurate characterization. This has significant implications for geotechnical engineering, as the SWCC directly influences numerical simulations of soil behavior under changing moisture conditions (Yao et al., 2021)

(Kang et al. 2020). Ultimately, the research concludes that while testing methods impact the precision of SWCC data, the selected empirical models provide reasonable approximations for practical applications, supporting improved predictions in geotechnical analysis.

The filter paper method, introduced by Gardner (1937) and standardized under ASTM D 5298, is widely used due to its cost-effectiveness and practicality, relying on filter paper to measure matric suction (Bicalho et al., 2007). The osmotic technique, first applied to geotechnical engineering by Kassiff and Ben Shalom (1971), uses semi-permeable membranes and polyethylene glycol (PEG) solutions to regulate suction, with improvements extending its range to 10 MPa (Delage et al., 1998; Blatz et al., 2008). The axis translation technique, commonly used in laboratory settings, applies controlled air pressure to impose suction up to 1.5 MPa, requiring robust confinement cells and fine-pore ceramics. Each method has distinct advantages and limitations, impacting the accuracy and applicability of SWCC measurements in geotechnical studies.

The relationship between soil water content and suction is commonly represented by the soil-water characteristic curve (SWCC), which plots volumetric moisture content as a function of matric suction (Li et al., 2020). Over time, experimental techniques for determining the SWCC have advanced, leading to the development of various analytical models designed to fit experimental data (Alnmr et al., 2023). Among these, the van Genuchten (1980) model is widely utilized to describe the relationship between water saturation and suction. This preference is largely due to its demonstrated applicability across a broad range of soil types, as confirmed by numerous studies. The pore pressure law is structured in the van Genuchten form, as follows:

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

Where S_e is effective saturation; $m=(1-1/n)$ is the shape parameters and P_0 is the reference capillary pressure.

The van Genuchten-Mualem (vG-M) model, which derives the hydraulic conductivity K_s from SWCC, often results in a highly nonlinear hydraulic conductivity function near saturation, particularly in fine-textured soils (Hayek, 2024). This pronounced non-linearity leads to steep gradients in the conductivity function, which can introduce numerical instability, convergence difficulties, and oscillations in the simulated suction and infiltration rates (Vogel et al., 2000). To mitigate these challenges, (Vogel et al. 1988) proposed modifications to the van Genuchten model to improve numerical stability under near-saturated conditions. Their approach involved refining the SWCC fit by introducing an apparent air-entry pressure (e.g., −0.2 kPa) and replacing the maximum water content with a fictitious value slightly exceeding the saturated water content.

Building on this, (Oh et al. 2015) proposed an alternative modification to the SWCC near saturation while maintaining the original parameter set of the van Genuchten model. In their approach, Ks was derived analytically by integrating the modified SWCC, ensuring improved numerical stability in infiltration simulations. Their research, which involved laboratory tests on unsaturated soils from five regions in Korea, demonstrated that the modified van Genuchten-Mualem (mvG-M) model provided superior predictions of the unsaturated hydraulic behavior of Korean weathered soils. The effectiveness of the mvG-M model was further validated through comparative analyses between experimental results and theoretical predictions, as illustrated in the modified SWCC diagram (Figure 01).

An arbitrary parameter, P_0' (equal to $0.02P_0$), was introduced to adjust the SWCC by tangentially extrapolating from the point (P_0', S_e').

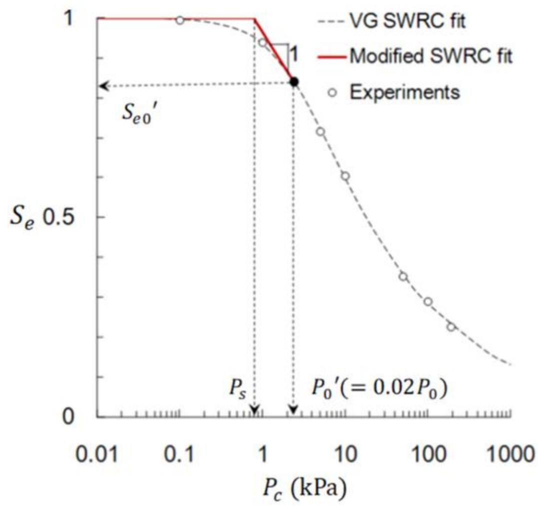

Fig. 1. A Comparison of the soil water characteristic curves (SWCC) using the modified van Genuchten model (Oh et al., 2015).

Subsequently, (Kang et al. 2020) further evaluated the mvG-M model's effectiveness for variably saturated soils, particularly fine-grained residual soils in Korea. Their findings indicated that the mvG-M model significantly improves numerical stability by mitigating abrupt decreases in hydraulic conductivity near saturation, a common issue with traditional models that can cause oscillations and divergence in numerical solutions. The mvG-M model achieves this by modifying the SWCC to ensure a smoother transition in *Ks* predictions, thereby enhancing its reliability for practical applications in geotechnical engineering and hydrology. The modified SWCC can be expressed as Equations (2)(3)(4) (Oh et al. 2015):

$$P_c = -P_0\left[\left(S_e\right)^{-\frac{1}{m}} - 1\right]^{1-m} \quad ,if\ S_e < S_0`, \tag{2}$$

$$P_c = -0.02P_0 \exp\left[a\left(S_e - S_0`\right)\right] \quad ,if \quad S_0` \leq S_e < 1, \tag{3}$$

$$0 \leq P_c < P_s, \quad ,if \quad S_e = 1, \tag{4}$$

Where

$$P_0 = \frac{\rho_w g}{\alpha} \quad , \quad P_s = -0.02P_0 \exp\left[a\left(1 - S_0`\right)\right] \quad , \quad a = \frac{\left[1 + \left(\alpha 0.02 P_0\right)^n\right]^{m+1}}{-mn(\alpha 0.02P_0)^n}$$

n= 1/(1-m) and *α* are the shape parameters.

Equation (5) defines the relationship between the mobility coefficient *K*, which represents permeability in the FLAC 2D, and the hydraulic conductivity K_s commonly used in Darcy's law to describe fluid flow based on hydraulic head. This relationship is expressed as follows:

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

In FLAC 2D, the formulation for relative permeability of the wetting fluid was introduced by van Genuchten, who derived it by integrating the SWCC, and applying a closed-form equation based on (Mualem, Y. 1976) capillary model, detailed in Equation (6):

$$k_r^w = \left(S_e\right)^b \left[1 - \left(1 - (S_e)^{\frac{1}{m}}\right)^m\right]^2 \tag{6}$$

Substituting the three equations (2)(3)(4) into the closed form equation (6) and we have the analytical solution for hydraulic conductivity based on the modified mVG-M model,

$$k_r^w = \left(S_e\right)^b \left[\frac{\left(\int_0^{S_0`} \frac{dS_e}{P_c} + \int_{S_0`}^{S_e} \frac{dS_e}{P_c} \right)^2}{\left(\int_0^{S_0`} \frac{dS_e}{P_c} + \int_{S_{e0}`}^{1} \frac{dS_e}{P_c} \right)^{2`}} \right] \qquad (7)$$

Conversely, the relative permeability for the non-wetting fluid (air) is described by (Lenhard et al., 1987), as expressed in Equation (8):

$$k_r^g = \left(1 - S_e\right)^c \left[1 - \left(S_e\right)^{\frac{1}{m}} \right]^{2m} \qquad (8)$$

In these equations, *b* and *c* are constants for water and air, respectively, both set to 0.5.

Researchers have extensively employed the shear strength reduction method (SSRM) for a range of applications. It is especially effective in addressing challenges related to complex geometries, seepage analysis, consolidation, and the interaction between hydrological and mechanical behaviors, often leading to more efficient solutions (Mburu et al., 2022; Hosseini et al., 2024). SSRM numerically identifies the critical failure surface by analyzing the development of failure shear strain zones resulting from suction variations due to rainfall over a given period . In software like FLAC 2D, the factor of safety (FoS) is calculated using the SSRM.

The analysis of unsaturated slopes integrates suction through constitutive models like the 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. The contributions of matric suction and pore-air pressure to shear strength are analyzed using Bishop's effective stress equation of unsaturated soils within the Mohr-Coulomb failure criterion, where effective stress and matric suction are treated as independent variables:

$$\sigma'_b = (\sigma - P_a) + \chi(P_a - P_w) \qquad (9)$$

Here, σ_b' represents the net normal stress, P_a is the pore-air pressure, P_w is the pore-water pressure, and χ is the matric suction coefficient. Alternatively, χ can be replaced by the degree of saturation (S_w+ S_a) (Hu, R., et al, 2018), leading to the modified equation:

$$\sigma'_b = \sigma - (P_w S_w + S_a P_a) \qquad (10)$$

Where S_w and S_a are the saturation degrees of the wetting and non-wetting fluids, respectively. The shear strength (τ_{max}) of unsaturated soil is expressed as:

$$\tau_{\max} = \sigma \tan\varphi' - (P_w S_w + S_a P_a)\tan\varphi' + c' \qquad (11)$$

In this expression, φ' is the effective internal friction angle, and c' is the effective cohesion.

3. Research Methods

3.1 Analysis method

The methodology adopted in this study integrates experimental characterization and numerical modeling to analyze the behavior of unsaturated soils, as illustrated in Figure (02). The hydraulic characterization involved measuring hydraulic conductivity *Ks* and determining the SWCC using the filter paper method, osmotic technique, and axis translation technique, with fitting parameters extracted for numerical modeling. These parameters were incorporated into the modified van Genuchten-Mualem model within FLAC using FISH scripting to simulate infiltration rates and the coupled hydromechanical response of unsaturated soils.

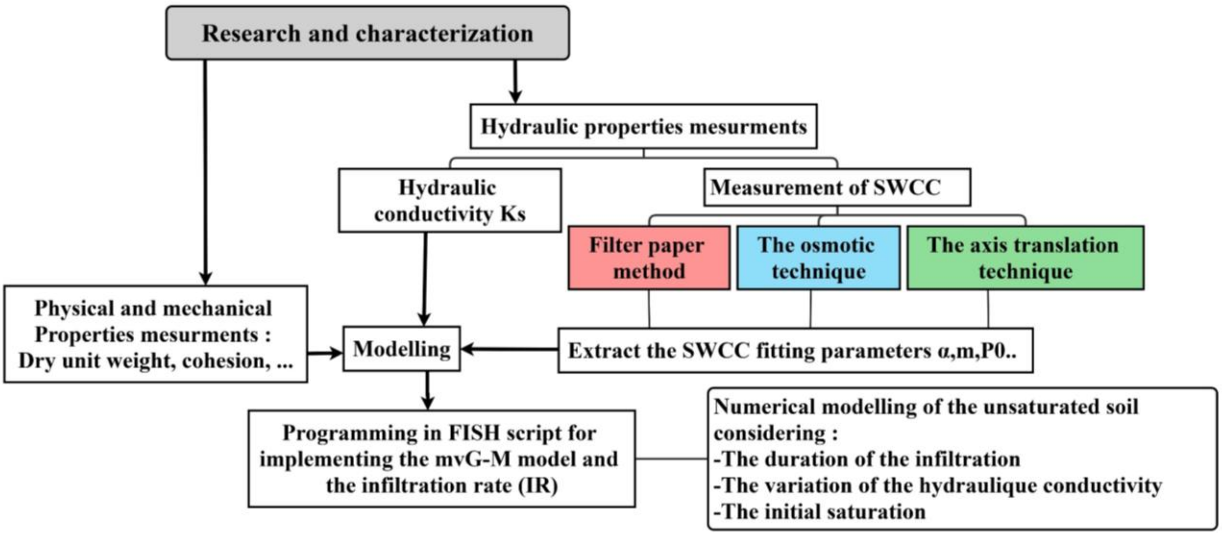

Fig. 2. Conceptual Flowchart

A major challenge in the numerical modeling process was the incompatibility between the mvG-M model, the relative permeability function, and the two-phase flow (tp-flow) option in FLAC. To overcome this limitation, the mvG-M model and the relative permeability function were manually implemented through FISH routines, ensuring accurate updates of SWCC and permeability relationships at each time step. Additionally, slope stability was assessed using the SSRM Method to compute the Factor of Safety. This method iteratively reduces shear strength parameters until slope failure occurs, providing a reliable evaluation of stability under varying infiltration conditions.

3.2 Soil properties and initial conditions

Soil samples were obtained from the Boulhaf El-Deir area in the Tebessa region, eastern Algeria. The soil primarily consists of silty sand (ML) and low-plasticity clay (CL). The characterization tests conducted included grain size analysis, determination of bulk density for undisturbed samples (ρ_b), moisture content (w_0), void ratio (e_0), specific gravity of soil particles (γs), and consistency limits. Hydraulic properties were assessed through the determination of saturated hydraulic conductivity. Strength parameters were evaluated using the direct shear Test, which provided the effective shear strength parameters of the Mohr–Coulomb criterion (φ' and c'). Table 01 summarizes the properties of the soil samples analyzed in this study.

Soils speciment were tested to establish their Soil-Water Characteristic Curve (SWCC) using three laboratory methods: the filter paper method, the osmotic technique, and the axis translation technique. The filter paper method (ASTM D5298) was applied using Whatman No. 42 papers to measure matric suction on samples compacted under Proctor conditions. The osmotic technique, based on semi-permeable membranes and polyethylene glycol (PEG) solutions, enabled control of higher suction ranges under long-term equilibrium. The axis translation method imposed suction by applying air pressure through fine ceramic porous stones, effective up to 1.5 MPa.

Table 1- Soil properties

Parameter	Value
Dry unit weight, γ_d (kN/m3)	18.00
Bulk modulus, K (kPa)	2.33×10^4
Shear modulus, G (kPa)	5×10^3
Cohesion, c (kPa)	12
Friction angle, φ	21
Hydraulic conductivity, Ks (m/sec)	7.98×10^{-5}

In this study, slope stability was evaluated using the factor of safety, with key factors influencing stability identified as rainfall duration, hydraulic conductivity, and initial saturation. The slope geometry used in the analysis is depicted in Figure 3, FISH scripts were employed to reproduce infiltration processes by simulating surface saturation of the slope under a uniform rainfall intensity of 5 mm/h applied along surfaces A–D. This setup incorporates potential seepage analysis and variable initial matric suction values, depending on the measurement method utilized.

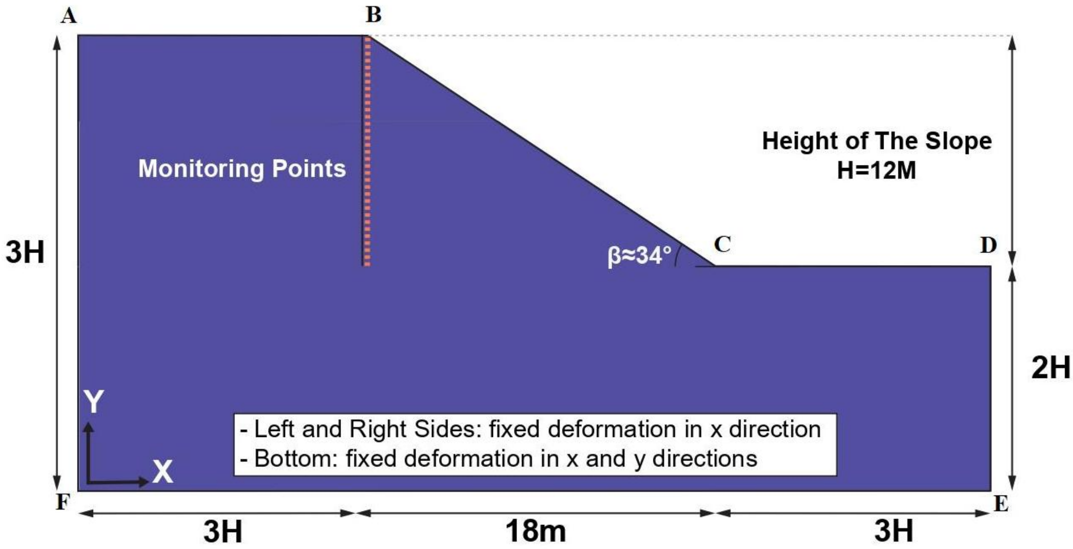

Fig. 3. Geometric Configuration and Boundary Conditions of the Analyzed Slope.

To define the boundary conditions, horizontal displacement was fixed along the left and right sides (AF and DE), while the bottom surface (FE) was fully constrained. The analyses were conducted with a consistent slope angle of approximately 34 degrees, which is lower than φ, as shown in Figure 3, and a Mohr-Coulomb criterion is used with an associated flow rule.

The coefficient K_0 cannot be generated in the first calculation phase because the slope has been in equilibrium for a long time. A factor of safety (FoS) calculation is performed, taking into account the duration of precipitation, hydraulic conductivity, and initial saturation. As saturation progresses, the equivalent pressure is recorded, and the ultimate load is determined when the soil reaches a plastic flow state dictated by the chosen criterion.

To ensure the reliability of the model and avoid unrealistic outcomes, a sensitivity analysis of the model dimensions was performed, refining its ability to represent critical features of the slope geometry and boundary conditions. In this model design, a domain extension of three times the slope height (3H) is used to prevent the critical slip surface from extending to the model boundaries. This approach ensures that boundary effects do not interfere with the failure line of the slope. The design is inspired by the geometric framework proposed by (Rahardjo et al., 2007).

4. Results and Discussions

4.1 Hydraulic variability from different methodologies

The results of the experiments for each testing method are presented in Figure 4. The experimental data reveal consistent trends in volumetric water content versus suction across all methods, with minor deviations observed. Notably, the matric suction values measured using the axis translation and osmotic techniques are slightly lower than the total suction values obtained from the filter paper method. While the filter paper method provides an estimate of total suction, the axis translation and osmotic techniques focus on matric suction, which may exclude certain components of total suction.

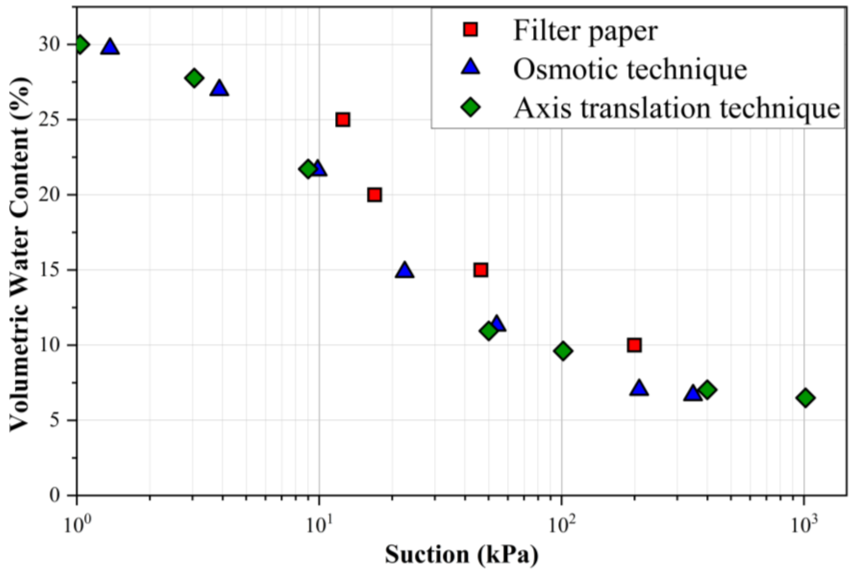

Fig. 4. Experimental Soil-Water Characteristic Curves (SWCC) from Diverse Measurement Approaches.

The SWCC fitting parameters, presented in Table 02, including the shape parameters (α and m), reference capillary pressure (P_0), and initial suction at 50% degree of saturation, exhibit notable variability across the testing methods. The filter paper method demonstrates lower α (0.13) and m (0.59) values compared to the osmotic technique (α = 0.15, m = 0.62) and the axis translation technique (α = 0.15, m = 0.66), indicating a less steep desaturation curve. Furthermore, the filter paper method records the highest reference capillary pressure (75.46 kPa), whereas the osmotic and axis translation techniques produce comparable and lower values (65.4 kPa). Similarly, initial suction at 50% degree of saturation is highest for the filter paper method (120.98 kPa), suggesting greater water retention estimates. In terms of model performance, the R^2 values present the coefficient of determination of the intuitive way to assess the goodness-of-fit for models obtained by nonlinear regression, the osmotic and axis translation techniques achieve superior fit quality, with higher R^2 values (0.99) compared to the filter paper method (0.93).

Table 2- Van Genuchten SWCC parameters from diverse measurement approaches.

SWCC fitting parameters	Technique		
	Filter paper	osmotic technique	Axis translation technique
Shape parameter, α	0.13	0.15	0.15
Shape parameter, m (Vga in flac)	0.59	0.62	0.66
Reference capillary pressure, P_0 (kPa)	75.46	65.4	65.4
Initial suction at 50 % degree of saturation (kPa)	120.98	101.4	98.12
R2= 1- SSE	0.93	0.99	0.97

The calibrated van Genuchten's models for the SWCC are shown and appear to provide good fit with every experimental result, SWCC comparisons show close agreement between the osmotic and axis translation techniques, while the filter paper method diverges slightly, particularly at lower suction levels.

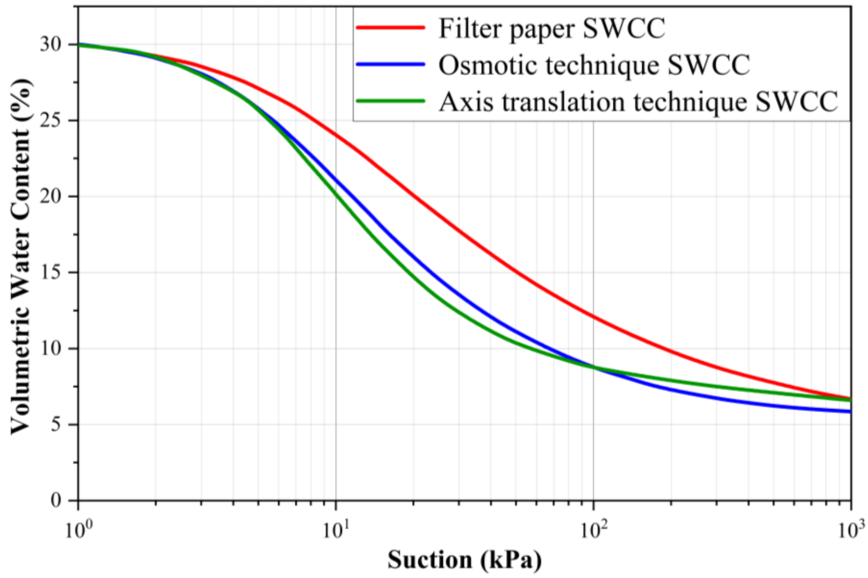

Fig. 5. Fitted SWCC from Diverse Measurement Approaches.

4.2 Numerical Model Validation

To ensure the accuracy and reliability of the numerical model developed for analyzing the hydromechanical response of unsaturated soils under wetting conditions, the results from (Kang et al. 2020) are employed as a benchmark. Kang's research provides a comprehensive analysis of the instability of homogeneous soil slopes, considering various rainfall intensities, soil properties, and slope geometries. This study serves as a solid reference point for validating and comparing the outcomes of the current research (see Figure 06).

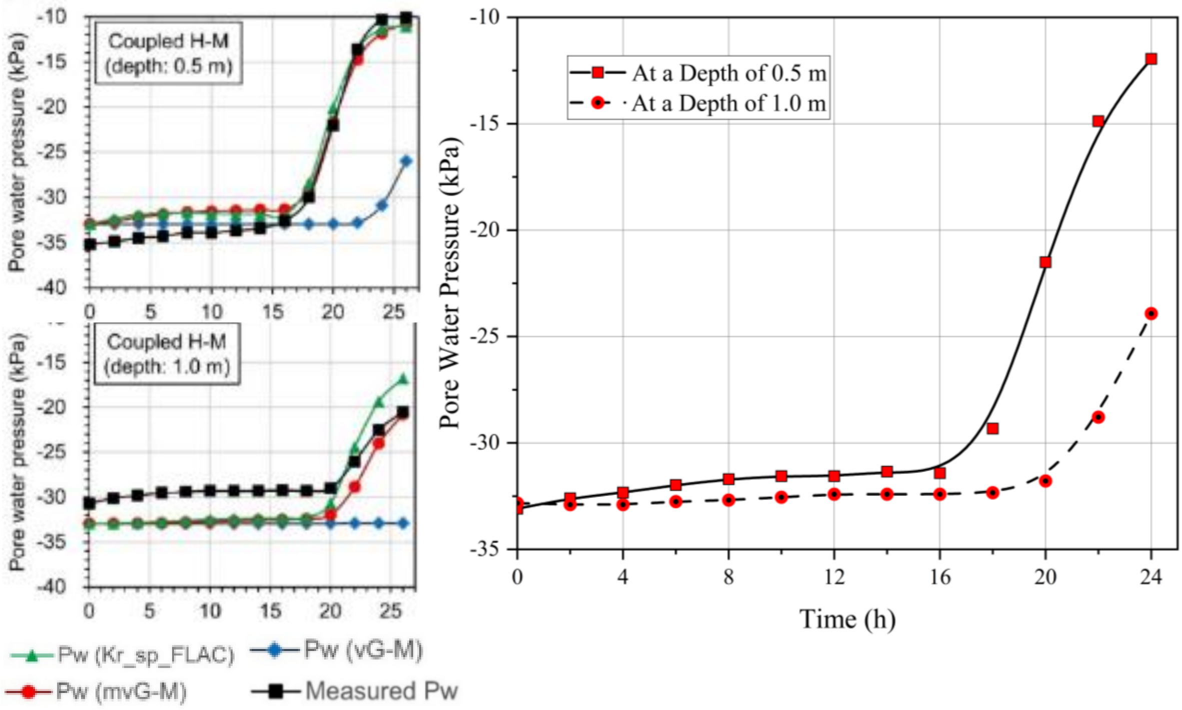

Fig. 6. Validation results of the modified van Genuchten-Mualem (mvG-M) model.

In Kang's study, a 24-hour rainfall event was analyzed to evaluate changes in pore water pressure at two depths (0.5 m and 1.0 m) using CHM models with three relative permeability formulations: the vG–M model, mvG–M model, and Kr–sp–FLAC (based on single phase flow model). The simulated pore water pressures were compared with field observations, revealing that the mvG–M model provided more accurate infiltration simulations under varying rainfall intensities, attributed to its smaller unsaturated hydraulic conductivity. While the Kr–sp–FLAC model demonstrated faster pore water pressure increases at greater depths, it exhibited higher deviations from observed values. Consequently, the mvG–M model was selected for the current study as the most suitable for simulating infiltration processes.

4.3 Influence of measurement techniques on the numerical results during infiltration

In this study, the three SWCC measurement techniques were employed to evaluate their impact on numerical simulations using a CHM model. To establish a realistic initial suction profile, a three-month CHM simulation without rainfall ($I_R = 0$) was conducted to achieve steady-state conditions for each SWCC type. Subsequently, a uniform rainfall intensity of 5 mm/h was applied for 48 hours, and the infiltration process was simulated using the CHM model coupled with the mvG–M model.

Figure 07 illustrates the saturation distribution with depth under different SWCC techniques. The filter paper method consistently predicts higher saturation, while the axis translation and osmotic techniques show a gradual decline, indicating differences in moisture retention capacity. After 24 and 48 hours of rainfall, all methods exhibit a notable increase in saturation, particularly in the upper 6 meters, where infiltration effects are strongest.

Despite significant initial variations, the post-infiltration saturation levels converge, showing minor discrepancies. For instance, at 1-meter depth, the filter paper method initially records 35% saturation, while the axis translation technique starts at 20%. However, after 24 hours of infiltration, their saturation values become nearly identical, differing by only 2%. This suggests that while initial SWCC conditions influence transient infiltration behavior, the final moisture distribution is less dependent on the measurement technique, highlighting the dominant role of soil hydraulic properties in long-term infiltration processes, since the soil is of the same type and reaches the same water content at full saturation regardless of the technique used to determine the (SWCC).

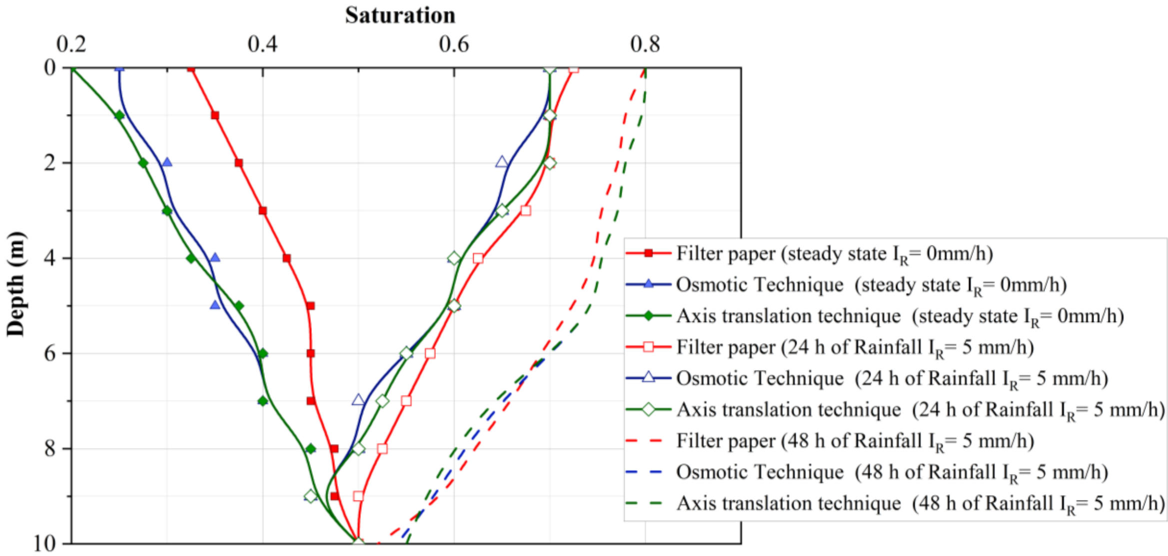

Fig. 7. Saturation distribution with depth in various SWCC measurement techniques.

The vertical suction profile variations at different depths are shown in Figure 9, using the three SWCC measurement techniques. Initially, under steady-state conditions ($I_R = 0$ mm/h), the filter paper method exhibits the highest suction values across all depths due to its ability to measure total suction. Conversely, the axis translation technique predicts lower suction values, indicating a more evenly distributed moisture content and improved capture of air-entry values, while the osmotic technique falls between the two, reflecting its ability to measure high suction ranges while maintaining realistic moisture retention predictions. After 24 hours of rainfall at 5 mm/h, all techniques indicate a significant suction reduction in the upper 5 meters. This trend persists after 48 hours of rainfall, where suction decreases further at all depths, the filter paper method still maintains slightly higher suction values, reflecting delayed saturation effects and lower predicted permeability, while the osmotic technique remains intermediate, confirming its balanced approach between air-entry value capture and extended suction range measurement. The progressive reduction in suction across all methods indicates that, despite initial differences, the influence of measurement techniques diminishes over time as soil approaches to saturation, reflecting a more realistic representation of field conditions.

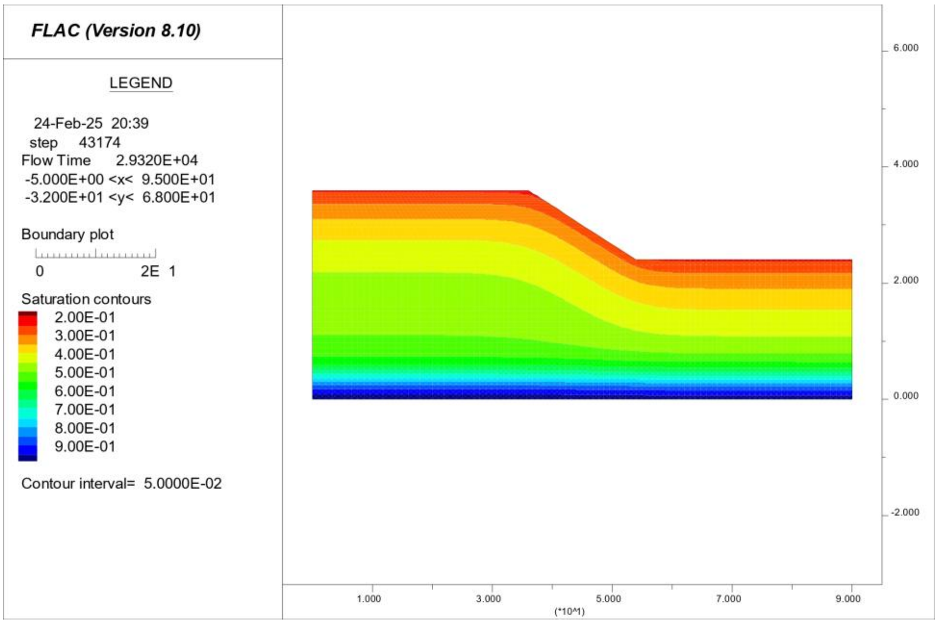

Fig. 8. Saturation distribution of the slope at the initial condition (Ir=0) in the case of the axis translation techniques.

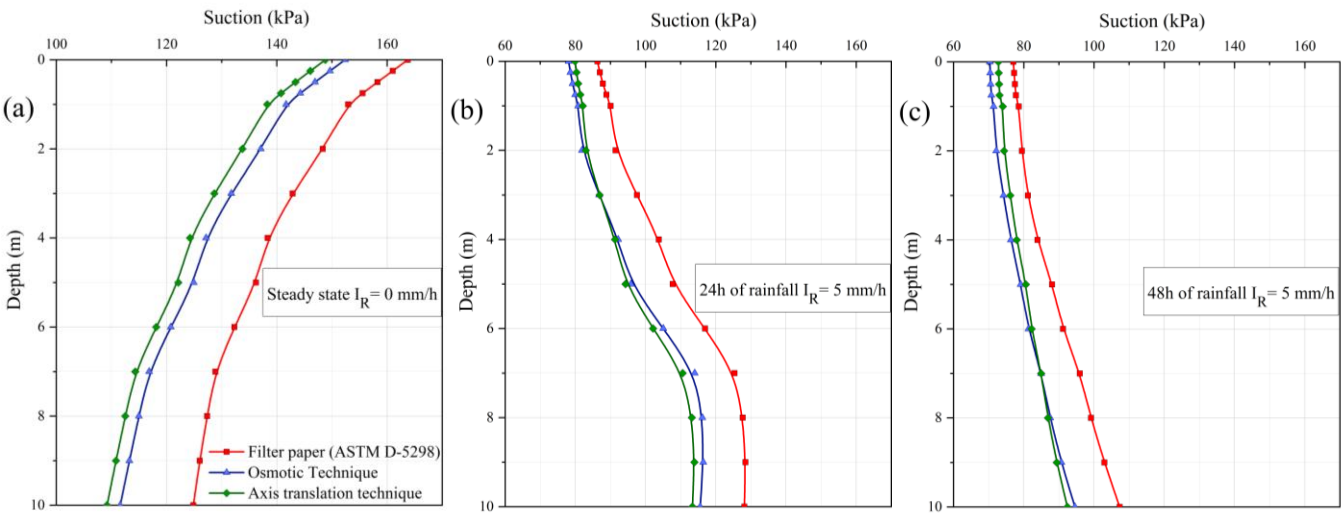

Fig. 9. Predicted vertical suction profile in various SWCC measurement techniques :(a) at the steady state condition 0mm/h; (b) with an intensity IR of 5mm/h for 24 hours; (c) with an intensity IR of 5mm/h for 48 hours.

The variation in the evolution of the safety factor across different measurement techniques underscores the sensitivity of slope stability analysis to the method used for determining soil hydraulic properties. As illustrated in Figure 10, The filter paper method, which measures total suction, yields a higher air entry value (AEV) compared to the osmotic and axis translation methods that measure matric suction. This higher AEV results in a higher factor of safety (FoS) when using the filter paper technique, as the increased air entry pressure contributes to greater stability in slope analysis. In contrast, the osmotic and axis translation methods, which focus on matric suction, produce lower AEV values and consequently result in a lower FoS. This results in an initial safety factor of 2.196 for the filter paper method, whereas the axis translation and osmotic techniques yield slightly lower values of 2.045 and 2.08, respectively. The influence of the difference between measurement techniques on the safety factor decreases over time as the soil approaches saturation. Notably, a higher air entry pressure corresponds to a greater reduction rate in the safety factor, as increased infiltration time delays full saturation. Overall, the safety factor exhibits a gradual decline due to the low saturated hydraulic conductivity, ranging between (4×10^{-5} and 12×10^{-5} m/s), which restricts the rate of water movement within the soil.

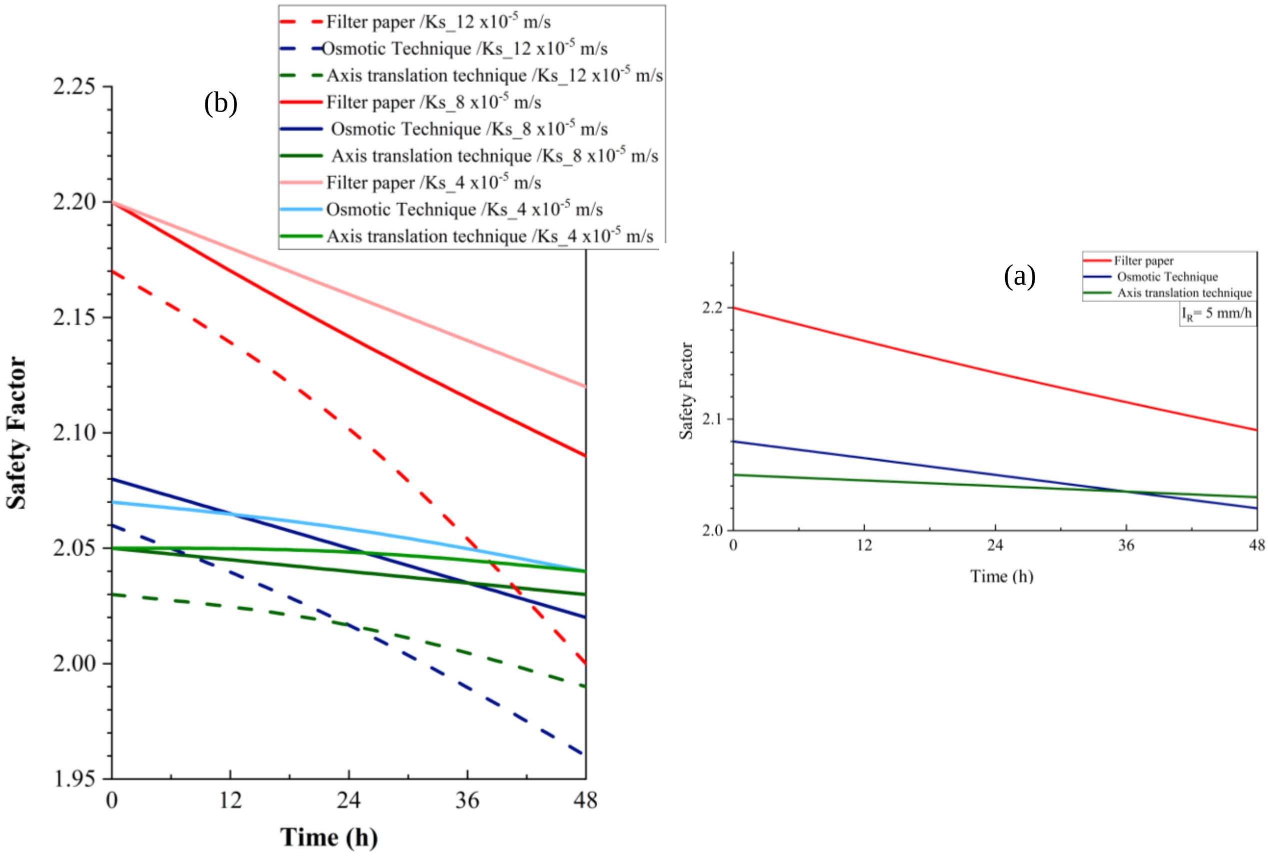

Fig. 10. (a) Safety factor variation over time for different SWCC methods. (b) under changing saturated hydraulic conductivity (from 4×10^{-5} to 1.2×10^{-4} m/s).

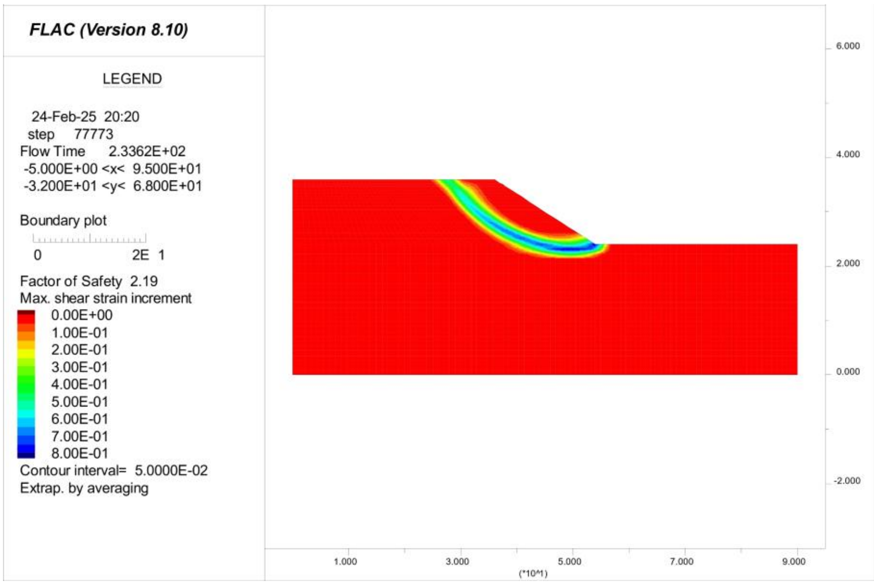

Fig. 11. FOS result after 24 h of rainfall (Ir=5 mm/h) in the case of the filter paper measurement technique.

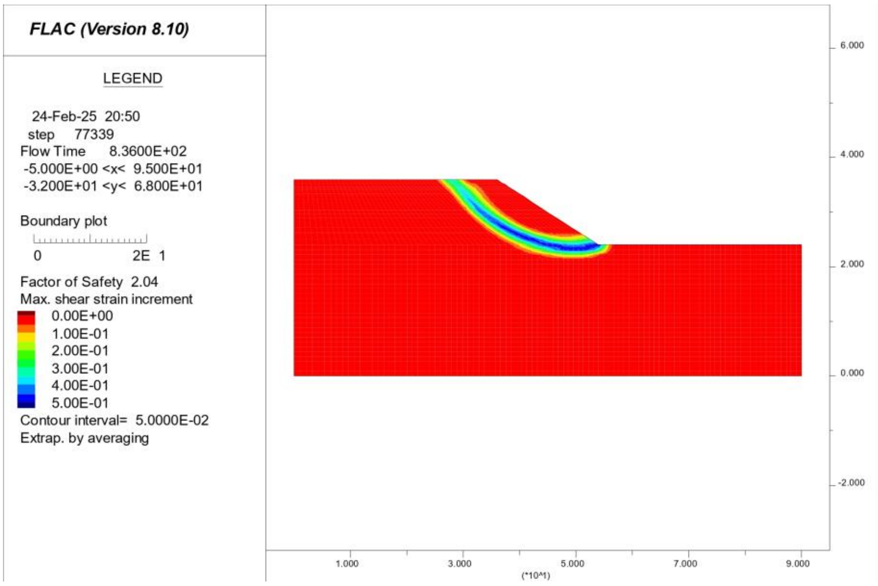

Fig. 12. FOS result after 24 h of rainfall (Ir=5 mm/h) in the case of the axis translation technique.

Figure 13 demonstrates that initial soil saturation has a more significant impact on the FOS evolution than the selected SWCC measurement method under a constant rainfall intensity of 5 mm/h. Across all methods, FOS decreases over time due to progressive infiltration, which reduces matric suction and weakens soil shear strength. Lower initial saturation levels (20–40%) exhibit higher initial FOS but experience a steeper decline over time, making them more susceptible to instability under prolonged precipitation, whereas highly saturated soils (80–90%) start with lower FOS values but undergo a more gradual reduction. Among the SWCC methods, the Axis Translation Technique consistently yields the highest FOS in drier conditions, followed by the Filter Paper Method, while the Osmotic Technique provides the most conservative estimates, likely due to differences in capturing soil suction variations.

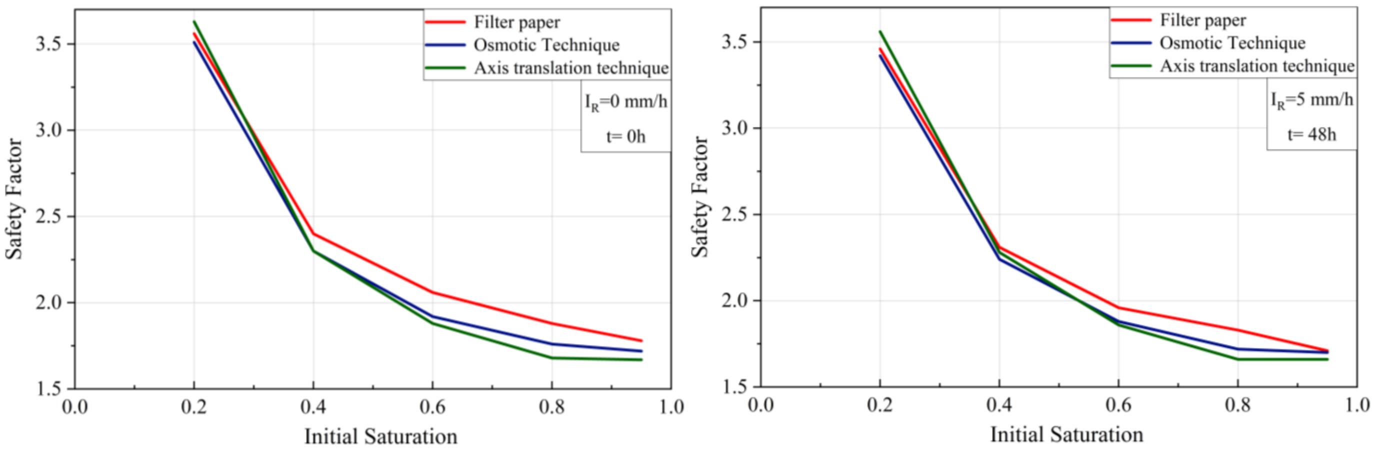

Fig. 13. Effect of initial saturation on safety factor evolution over time and under various SWCC methods.

Discussion

The findings highlight that while the choice of SWCC measurement technique affects hydromechanical analyses, its influence is most pronounced during the early stages of infiltration and gradually diminishes as soils approach saturation. The filter paper method, by capturing total suction, tends to initially overestimate slope stability, whereas the axis translation and osmotic techniques, which measure matric suction, yield lower safety factors and faster infiltration predictions, representing more conservative or worst-case scenarios. Over time, however, the differences among methods converge, indicating that long-term slope stability is governed primarily by intrinsic soil hydraulic properties and initial saturation rather than the specific testing approach.

From an engineering perspective, the filter paper method is suitable for cost-effective and conservative assessments but requires careful calibration at low suction ranges; the axis translation technique provides reliable parameters where accurate determination of air-entry values is critical; and the osmotic method delivers balanced predictions across a wide suction spectrum. Overall, integrating multiple techniques or adopting hybrid approaches could enhance laboratory characterization and numerical modeling, thereby improving the reliability of geotechnical predictions.

5. Conclusion

This study systematically compared Soil-Water Characteristic Curves SWCC obtained using measurement techniques (filter paper method) and imposition methods (axis translation and osmotic techniques) to evaluate their impact on infiltration processes and slope stability. The results indicate that minor variations in Air-Entry Value and van Genuchten parameters arise due to differences in suction measurement approaches. The filter paper method, despite being cost-effective and capable of measuring both matric and total suction, exhibits limitations at low suction values (<10 kPa), requiring complementary techniques for improved accuracy. Furthermore, its sensitivity to weight fluctuations and ongoing calibration debates underscores the necessity for careful application in geotechnical studies.

Numerical simulations using the coupled hydromechanical model and the mvG–M model reveal that the filter paper method predicts higher initial suction values, leading to delayed infiltration and a more conservative estimation of safety factors. Conversely, the osmotic and axis translation techniques, which focus on matric suction, yield lower reference capillary pressures, faster infiltration, and slightly lower safety factors, with a maximum recorded difference of 0.15 in FoS between the filter paper and axis translation methods. However, as rainfall infiltration progresses and the soil approaches saturation, these discrepancies diminish.

The reported results already represent averaged values, and repeating tests for error margins was beyond the scope of this work; nonetheless, these averages provide a reliable basis for the comparisons and modeling conducted. For preliminary analysis, indirect methods such as the filter paper technique can provide practical estimates, while axis translation and osmotic techniques are more suitable for detailed or safety-critical designs due to their higher accuracy and reliability. In cases where a broad suction range and cross-validation are required, the combined use of multiple methods is recommended, as their complementary strengths improve the reliability of SWCC characterization.

While the choice of SWCC measurement technique slightly influences the evolution of the FoS under transient infiltration conditions, initial saturation remains the primary factor controlling slope stability. These findings emphasize the importance of selecting an appropriate SWCC measurement technique based on the specific requirements of hydromechanical modeling, particularly in slope stability assessments where initial soil conditions play a crucial role.

Future research should focus on integrating multiple SWCC measurement techniques to overcome individual methods' limitations and develop hybrid approaches that enhance accuracy for infiltration modeling and geotechnical stability predictions. In particular, studies should investigate the effect of different SWCC methods on the volumetric behavior of unsaturated soils, exploring variations in shrinkage, swelling, and collapse potential. Additionally, long-term analyses should be conducted to assess the impact of SWCC variability on slope stability under prolonged wetting-drying cycles, while refining calibration protocols and sensitivity analyses for numerical models to improve prediction reliability.

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