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IMPACT OF INTENSE RAINFALL ON SLOPE STABILITY: ASSESSMENT AND DESIGN CONSIDERATIONS

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Abstract

This paper examines and evaluates the impact of intense rainfall on slope stability and proposes an approach for incorporating this influence into slope design. The main objective is to demonstrate that the infiltration of atmospheric water affects the natural moisture content of the soil, leading to a reduction in the initial suction and finally decreasing the shear strength of unsaturated soils. Therefore, the use of a more advanced concept for numerical slope stability analysis is recommended, in which the mechanical and hydraulic behavior of the soil is analyzed simultaneously as a multiphase system over time through a fully coupled flow–deformation analysis. Such an approach represents one of the most advanced and realistic types of analysis, capable of explaining the phenomena that occur as a result of seepage processes, changes in the degree of saturation, and variations in the physico-mechanical properties of the soil.

For the successful application of such analyses, it is necessary to have a proper understanding of the hydraulic characteristics of the soil, their constitutive relationships, as well as the intensity of rainfall. The stability analysis of sandy materials shows that changes in the degree of saturation begin immediately after the onset of rainfall due to infiltration processes. After three hours of intense rainfall with an intensity of 30 mm/h, the effect of moisture change extends to a depth of approximately 1.0 m, while the upper 0.5 m of the slope becomes fully saturated. The highest suction occurs in the zone where the degree of saturation is lowest, approximately 2.0 m below the crest of the slope. The greatest reduction in suction is observed at the slope surface, where the material becomes saturated due to the influence of rainfall. The maximum deformations occur at the crest of the slope. As a result of the reduction in the shear strength parameters of the soil, the factor of safety decreases from 1.63 to 1.59 under the influence of rainfall.

Keywords

Slope stability, intense rainfall, interaction, infiltration, numerical analysis.

1 Introduction

Slope instability is often caused by atmospheric influences such as rainfall and snowfall, freeze–thaw cycles, wetting and drying processes, and similar environmental factors. In the literature, this phenomenon is commonly referred to as soil–atmosphere interaction, and its effects have become increasingly pronounced due to climate variability and ongoing climate change. Atmospheric influences can trigger flow-type failures, landslides, or significant erosion of both natural and man-made slopes in soil as well as rock environments. Water infiltration may also lead to numerous other adverse effects and engineering problems, such as volume changes in collapsible and expansive soils, reduction in shear strength and bearing capacity, and soil loss due to coastal erosion.

This paper presents several examples that support this hypothesis and provides a detailed description of the associated problems. In Figure 1 (left), a slope failure is shown that occurred as a result of wetting of a berm where a surface water drainage channel is located. However, the channel became filled with eroded material from the slope above. The ponded water on the berm infiltrates into the slope, generating concentrated flow paths which, as a result of suffosion, lead to the development of a deeper slip surface. The right image illustrates a long-term process of deposition of fine-grained material resulting from the surface weathering of rocks.

Figure 1. Examples of slope instability along the Miladinovci–Štip highway: failure of a slope section caused by berm wetting (left) and long-term erosion resulting from atmospheric effects (right).

The aim of this paper is to contribute to the engineering understanding of slope stability analysis that depends on the interaction between soil and atmospheric conditions. In this context, a more advanced concept for slope stability analysis will be presented, which considers the mechanical and hydraulic behavior of the material as a multiphase system evolving over time.

For its application, in addition to the conventional mechanical parameters, it is necessary to determine the hydraulic characteristics of the soil, the loading effects induced by rainfall, as well as to employ appropriate monitoring equipment capable of defining the variation of key parameters that influence both the local and global stability of slopes (Susinov & Josifovski, 2018).

2 Causes of slope instability due to rainfall

Slope instability during intense rainfall occurs primarily due to water infiltration, which reduces soil strength as a result of the decrease in suction in previously unsaturated soils (Fredlund & Rahardjo, 1993). Recent studies have shown that changes in the water content within soil pores significantly alter soil behavior to an extent that the classical theory of soil mechanics is no longer fully adequate to describe these processes. Consequently, the theory has been extended in order to better understand the behavior of partially saturated soils through the introduction of additional parameters and constitutive relationships.

The hydrostatic equilibrium under steady-state flow conditions in unsaturated soils differs from that in saturated soils, depending on whether the water moves upward (evaporation) or downward toward the groundwater table (infiltration).

Prolonged dry periods promote soil desiccation and the formation of tension cracks as a result of intense surface evaporation on the slope, which increases the hydraulic conductivity of the surface layers. On the other hand, pore water pressure becomes negative, contributing to an increase in the shear strength of the soil.

Open cracks with high permeability facilitate faster infiltration of rainfall into the slope. The negative pore pressure, or matric suction, of the unsaturated soil that maintains slope stability decreases as saturation increases during wet periods. As a result, the degree of saturation rises, the shear strength of the soil decreases, and the overall slope stability is reduced to a level that may trigger slope failure.
The intensity of rainfall does not necessarily match the infiltration rate of water into the soil, as it depends on the soil's infiltration capacity. When the rainfall intensity exceeds the soil's infiltration capacity, ponding or surface runoff may occur, which can lead to erosion. However, this does not happen immediately at the onset of rainfall, because during the initial period, the soil's infiltration capacity is relatively high and all the water infiltrates. This is followed by a phase in which the soil becomes increasingly wet, and the infiltration capacity decreases significantly.

3 Approaches to slope stability analysis

In recent years, engineering practice in the construction of highways, railways, canals, pipelines, dams, and tailings facilities has required that slopes be analyzed under the influence of atmospheric conditions, taking into account the potential risks associated with such hazards. This is supported by recent research indicating that the water content in soil pores has a significant impact on slope stability. Consequently, several aspects of classical soil mechanics need to be extended in order to accurately describe the behavior of unsaturated soils, particularly under varying moisture conditions.

Slope stability is commonly analyzed using established methods such as limit equilibrium analysis, sensitivity analysis, probabilistic approaches, and numerical methods. The influence of rainfall is traditionally accounted for in these analyses through a rise in the groundwater table or changes in flow paths, although data on groundwater level increases are often insufficient in cases of shallow landslides. During intense rainfall events, shallow slip surfaces, typically parallel to the slope surface, are most frequently observed. Therefore, the infinite slope method can also be applied in stability analysis.

There are methods that can be modified to incorporate changes in pore pressure derived from measurements or from analytical and/or numerical infiltration analyses. However, these standard steady-state uncoupled methods for unsaturated soils often struggle to accurately reflect real conditions due to neglecting the interaction of the fluid moving through the soil pores.

More realistic results are obtained using methods or models that consider the interaction between the solid, liquid, and gaseous components of the soil volume (transient coupled methods), particularly for problems related to infiltration. Successful application of these methods requires knowledge of the soil's shear strength parameters, hydraulic characteristics, and rainfall properties (Zhang et al., 2018).

In engineering practice, the mechanical and hydraulic stability of soils is typically considered separately. However, when analyzing slope stability with the inclusion of soil–atmosphere interaction, these two aspects must be considered jointly. Fully coupled flow–deformation analysis accounts for the behavior of unsaturated soils and the matric suction in the unsaturated zone above the groundwater table. This represents the most advanced and realistic type of analysis, as it considers reduced hydraulic conductivity and the degree of saturation within the unsaturated zone. Such a coupled approach can explain phenomena occurring as a result of processes in unsaturated soils, including infiltration and changes in the physico-mechanical parameters, particularly the moisture content.

Performing this type of analysis requires software capable of solving time-dependent processes, such as PLAXIS, SOFiSTiK, or GeoStudio, all of which employ the finite element method. Defining the material behavior requires the application of constitutive laws that describe the relationships between multiple variables (e.g., stresses, strains, and other relevant parameters).

4 Key parameters and models for analysis

In addition to the mechanical soil parameters obtained through standard laboratory or field tests, it is necessary to define the hydraulic properties of the soil, which are critical for such analyses. The most important parameter for slope stability analysis is suction and its relationship with moisture content or degree of saturation. As moisture increases due to infiltrating water, suction decreases, leading to a reduction in slope stability.

Hydraulic conductivity in unsaturated soils is not constant and depends on the degree of saturation. As the moisture content decreases in initially saturated soil due to the intrusion of air into the pores, the hydraulic conductivity also decreases.

The constitutive relationship between suction and water content is described by the Soil Water Retention Curve (SWRC). Its shape depends on the soil's material properties, including pore size distribution, particle-size composition, compaction, organic matter content, clay fraction, and the influence of the mineralogical composition on water retention (Lu & Likos, 2004). The following figure presents SWRCs for different soil materials.

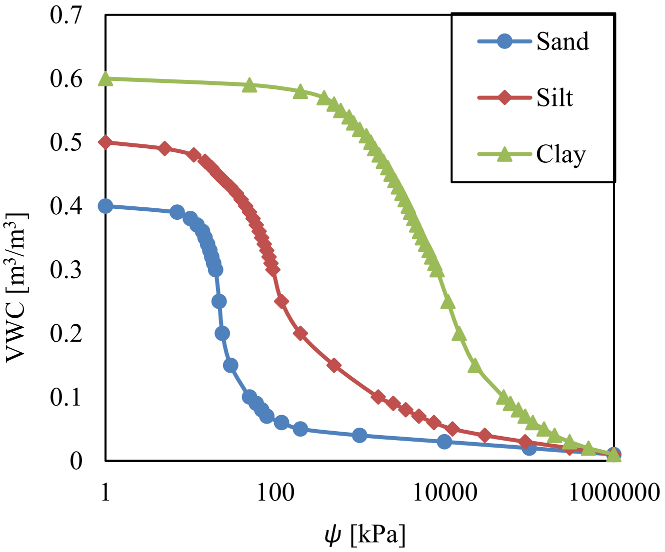

Figure 2. Soil Water Retention Curves for three different soil types.

The Soil Water Retention Curve (SWRC) can be divided into three segments with different slopes, corresponding to a degree of saturation ranging from 0 to 1.0. These segments illustrate four distinct saturation (moisture) phases as the matric suction increases from zero at full saturation.

In the first phase, the soil is fully saturated, and moisture loss occurs due to the curvature of the menisci. In the next phase, referred to as the quasi-saturated phase, air enters the largest pores, and suction begins to increase. When the so-called air-entry pressure (AEP) is reached, the curve transitions to the next phase, dominated by capillary effects, with a continued increase in suction.

In the final, residual phase, the soil contains a small amount of water, which is dependent on the contact surfaces of the solid particles as well as their size and shape. Water exists as thin films around the grains, retained by electrostatic forces between the particles.

The relationship between unsaturated hydraulic conductivity k_w and suction ψ can be determined using measurements from a HYPROP device. An example for a sandy soil is presented in Figure 3 (left). The relationship between unsaturated hydraulic conductivity k_w and volumetric water content θ (VWC) for the same material is shown in Figure 3 (right).

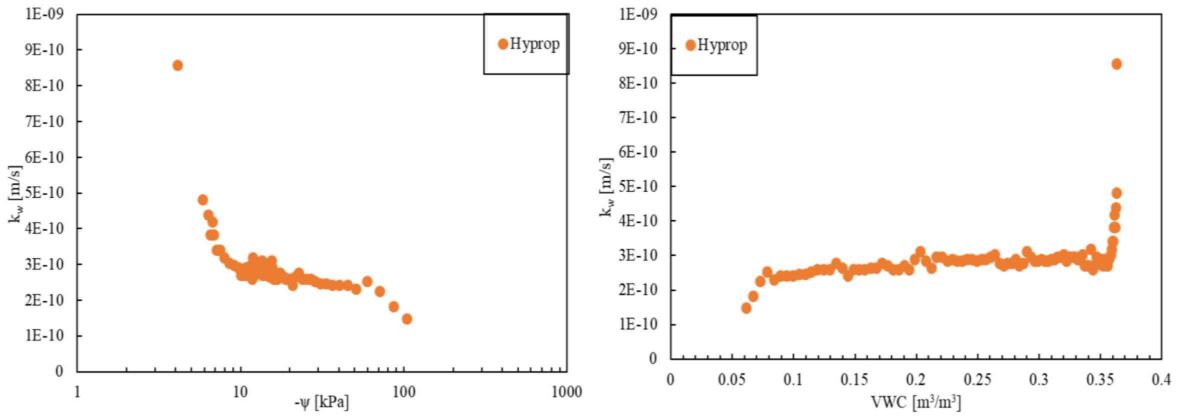

Figure 3. Measured unsaturated hydraulic conductivity kw using the HYPROP device as a function of suction (left) and volumetric water content (right).

The determination of the design rainfall intensity and its duration is obtained through a statistical analysis of recorded rainfall for the study area. This analysis defines the probability of occurrence of maximum rainfall events and their corresponding durations.

5 Numerical modeling

To incorporate these data into numerical modeling software, constitutive models are used to describe the relevant relationships. For representing Soil Water Retention Curves (SWRCs), the most widely used models include those proposed by Brooks and Corey (1964), Van Genuchten (1980), Fredlund and Xing (1994), Kosugi (1996) for log-normal pore-size distribution, Durner (1994) for bimodal distribution, and Seki (2007) for bimodal log-normal pore-size distribution.

Most of these functions are empirical in nature, although they may include parameters with physical meaning. These models are based on the function of effective (normalized) saturation, or reduced water content S_e, expressed as a function of suction:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{1}$$

where θ_s is the water content at full saturation and θ_r is the residual water content. If θ is expressed, it can be written as:

$$\theta = \theta_r + S_e \cdot (\theta_s - \theta_r) \tag{2}$$

The value of S_e ranges between $0 \leq S_e \leq 1$, where $S_e=0$ when $\theta=\theta_r$ and $S_e=1$ when $\theta=\theta_s$.

In addition to describing the relationship between suction and water content, these models can also be used to estimate the unsaturated hydraulic conductivity k, i.e., the permeability of the soil. They are generally classified into three groups: empirical models, such as that of Richards (1931); macroscopic models, such as Brooks and Corey (1964); and statistical models, such as Mualem (1976).

The first two groups rely primarily on measured data, whereas the third group utilizes information derived from the Soil Water Retention Curve (SWRC).

In general, the unsaturated hydraulic conductivity k_w above the air-entry value is approximately equal to the saturated hydraulic conductivity k_s. In this study, a sandy soil material was used, and its properties are presented in Table 1.

Table 1. Material Properties Used in the Analysis

Material	Conditions	γ_{unsat} [kN/m^3]	e_{init} [/]	E_{oed} [kN/m^2]	ν [/]	c' [kN/m^2]	ϕ' [°]	k_x=k_y [m/s]
Sand	Drained	19.0	0.7	8000	0.3	2	28	1x10^{-3}

The mechanical behavior of the material was simulated using the Mohr–Coulomb failure criterion, while the hydraulic behavior was modeled using the Van Genuchten (1980) model through the predefined “Hypres” dataset in PLAXIS 2D (Galavi, 2010), which is based on a database of various soil types.

Figure 4 presents the general classification, as well as the relationships between the two main hydraulic functions: degree of saturation S_r versus suction ψ and relative hydraulic conductivity K_r versus suction ψ, respectively.

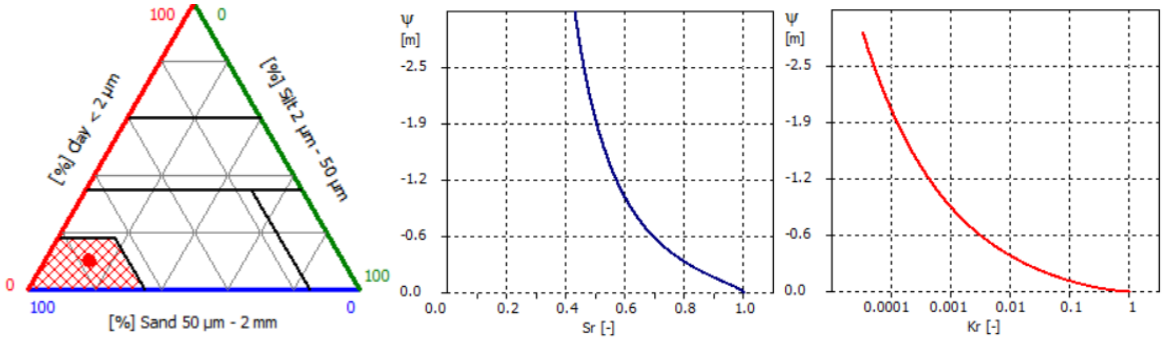

Figure 4. Material classification and relationships between hydraulic parameters.

The slope stability analysis under intense rainfall conditions was performed for a slope with a height of 10 m and an inclination of 1:1.5, which is commonly encountered in road infrastructure projects in Macedonia. The geometry of the model is presented in the following figure.

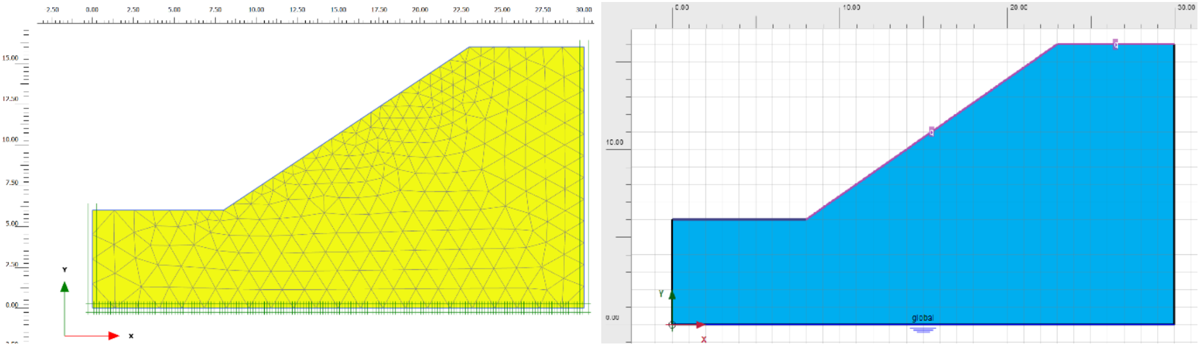

Figure 5. Geometry of the numerical model with applied boundary conditions.

Standard boundary conditions were applied on the bottom, left, and right sides of the model: restrained deformations (normal/fully fixed BC) and no-flow boundaries (closed BC). On the horizontal section above the slope and the slope surface, infiltration BC was applied, while a seepage BC was assigned to the horizontal section to the left of the slope.

The rainfall intensity was set to 30 mm/h, which is a common value recorded at many meteorological stations throughout North Macedonia. The representative intensity is based on a statistical analysis of measured rainfall for a given duration and probability of occurrence (Susinov et al., 2019). The analysis was performed for a rainfall duration of 3 hours.

The analysis was performed in several consecutive stages:

- Initial phase (Gravity loading): to simulate the initial distribution of stresses and pore pressures.
- Fully coupled hydro-mechanical analysis: simulation of flow and deformations as a function of time.
- Safety factor evaluation (Safety): by reducing the soil strength parameters after the two previous phases.

6 Results

The following presents the results obtained from the conducted analysis in the two phases. The most relevant parameters in such analyses include the changes in suction, degree of saturation, deformations, and the occurrence of plastic points and tensile points.

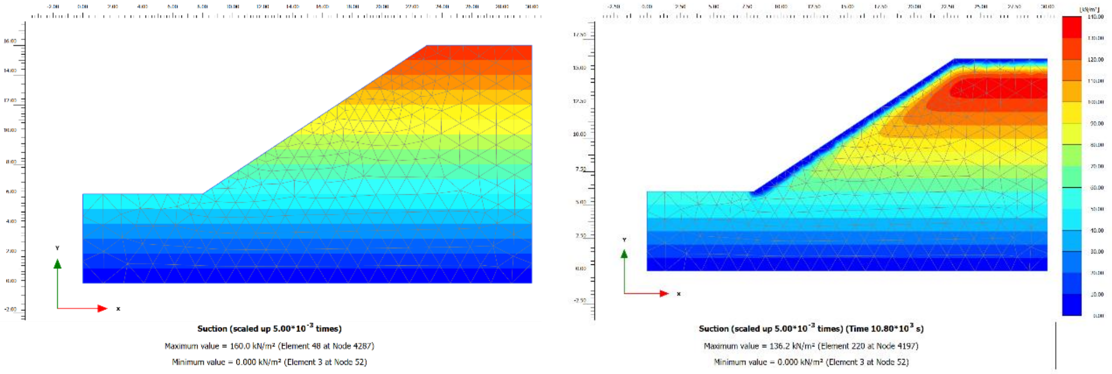

Figure 6. Changes in suction within the model.

From the suction diagram at different times during the simulation, it can be concluded that the maximum suction in the initial phase of the analysis reaches 160 kPa and occurs at the top of the slope as a negative pore pressure, depending on the groundwater level, which in this case coincides with the bottom boundary of the model. After rainfall, the suction decreases to 136.2 kPa at approximately 2.0 m below the slope crest. A cross-section through the slope crest would more clearly illustrate the reduction in suction.

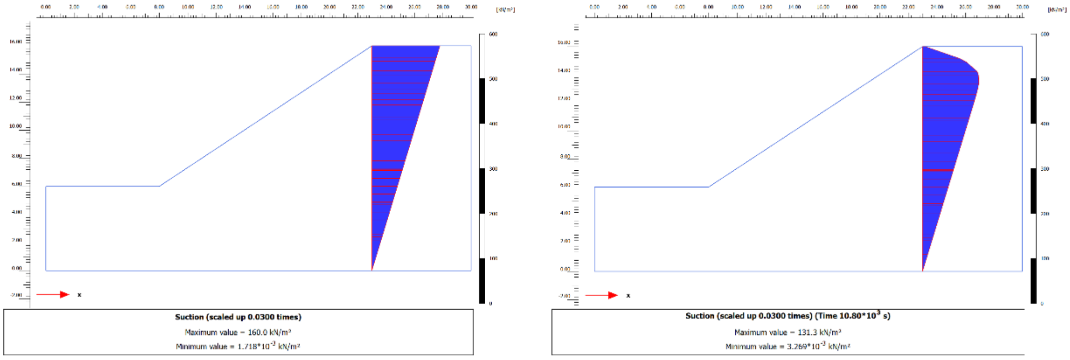

Figure 7. Variation of suction along a cross-section at the slope crest.

The greatest reduction in suction occurs at the slope surface, where the material becomes saturated due to rainfall, with suction approaching 0 kPa. Suction is related to the degree of saturation S_r hrough the defined function. The rate of saturation depends on the rainfall intensity, the hydraulic boundary conditions, and the soil hydraulic conductivity, which itself is a function of suction.

The following figure presents the changes in the degree of saturation before and after the rainfall event.

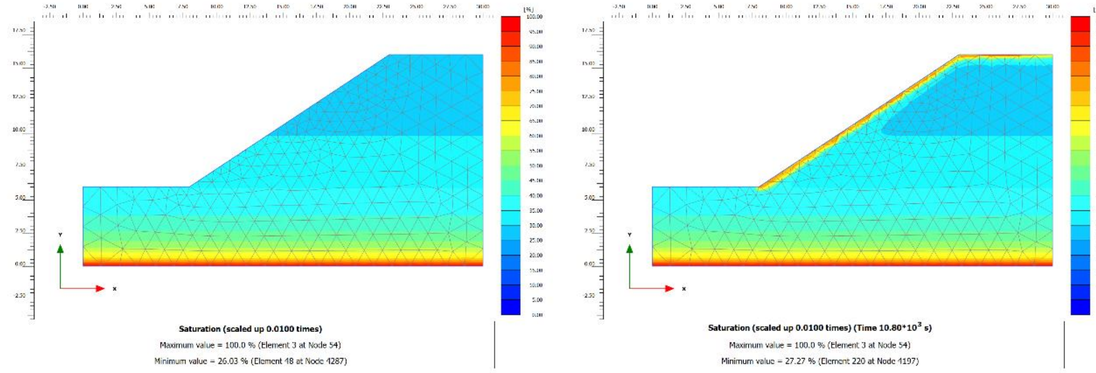

Figure 8. Changes in the degree of saturation within the model.

The change in the degree of saturation begins immediately after the application of rainfall due to infiltration. The minimum degree of saturation is 27.27% and occurs in the zone where suction is highest. As infiltration progresses, the unsaturated zone decreases, while the surface layer becomes saturated (Figue 9). After three hours of rainfall, the effect on moisture content extends to a depth of 1.0 m, with the top 50 cm fully saturated.

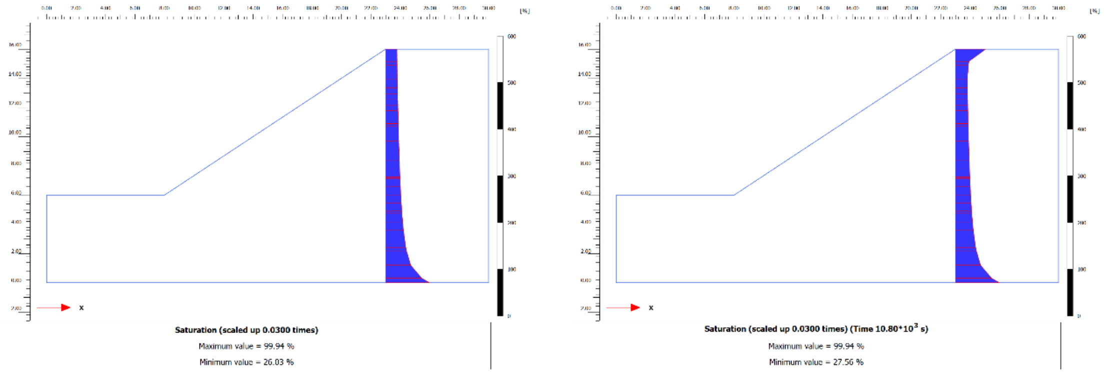

Figure 9. Variation of the degree of saturation along a cross-section at the slope crest.

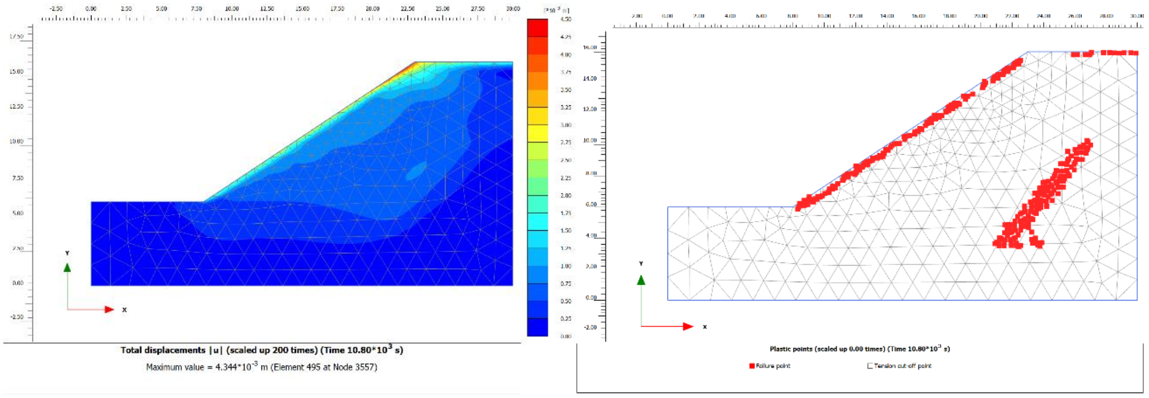

Figure 10. Total slope deformations and the occurrence of plastic and tensile points after rainfall.

The development of deformations and the occurrence of plastic and tensile points are shown in Figure 10. The maximum slope deformations occur at the crest and reach 4.34 mm.

In the final phase, a slope stability analysis (Safety) was performed for both phases by reducing the soil strength parameters. The resulting factor of safety is 1.63 for the pre-rainfall condition, and decreases to 1.59 after a single rainfall event.

7 Conclusion

Slope destabilization is increasingly recognized as being caused by climatic variations and changes, particularly through extreme rainfall events. Such interactions are often not considered in standard engineering practice for slope stability analysis, which has proven to be a limitation during the operational phase of infrastructure projects. Numerous cases of flow, sliding, and significant erosion have been observed, not only in soil slopes but also in rocky environments. This study provides examples that support this hypothesis and offers a detailed description of the issues and the causes of slope instability.

Slope stability is commonly analyzed using well-known methods such as limit equilibrium analysis, sensitivity analysis, probabilistic approaches, and numerical methods. These standard steady-state uncoupled methods often face difficulties in accurately representing unsaturated soils, due to the neglect of fluid–soil interaction and time-dependent infiltration. Therefore, it is recommended to use transient coupled methods, which account for the interaction between the solid, liquid, and gas phases within the soil volume. This approach represents the most advanced and realistic type of analysis, capable of explaining the phenomena that occur as a result of filtration processes, changes in moisture content, and variations in physical–mechanical properties.

In this study, numerical modeling of slope stability was conducted, incorporating the soil–atmosphere interaction through intense rainfall events. The numerical analysis performed in PLAXIS 2D shows that, in the initial phase, the slope is partially saturated. During the coupled hydro-mechanical analysis, considering the rainfall effects over time, the distribution of the degree of saturation and suction changes. The rate of saturation depends on the rainfall intensity, the permeability of the hydraulic boundaries, and the soil hydraulic conductivity, which itself is a function of suction.

Changes in the degree of saturation begin immediately after rainfall due to infiltration. As infiltration progresses, the unsaturated zone decreases, while the surface layer becomes saturated. After three hours of rainfall, the effect on moisture content extends to a depth of 1.0 m, with the top 50 cm fully saturated. The minimum degree of saturation occurs in the zone where suction is highest. Suction is related to the degree of saturation through a defined function, so the maximum suction occurs in the zone with the lowest saturation, approximately 2.0 m below the slope crest. The greatest reduction in suction occurs at the surface, where the material becomes saturated due to rainfall, with suction approaching 0 kPa. As suction decreases, pore pressure increases, leading to the formation of relatively shallow slip surfaces. The maximum slope deformations occur at the crest and reach 4.34 mm. As a result of the slope safety analysis performed for both phases by reducing the soil strength parameters, the factor of safety decreases from 1.63 under pre-rainfall conditions to 1.59 after a single rainfall event.

As a general conclusion, the results obtained support the initial hypothesis that rainfall can have a significant impact on the destabilization of near-surface soil layers on slopes. Initially, this may manifest as erosion, which can evolve into local instability, and ultimately lead to global failure and slope sliding.

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