

Evaluation of unsaturated slope stability under rainfall infiltration based on experimental and numerical modeling

Évaluation de la stabilité des pentes non saturées sous infiltration de pluie basée sur une modélisation expérimentale et numérique

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ABSTRACT: The presented paper contributes to the definition of the hydro-mechanical behavior of unsaturated soils while evaluating the problem of rainfall-induced slope instabilities. The slope instabilities in the Western Balkan countries have significantly increased in the past couple of years, due to climate change effects and its influence on the slope stability. Besides the arid climate, the increased manifestations of intense rainfalls often equal to monthly precipitation are the main contributing factors. Therefore, in North Macedonia, an assessment study has been initiated to re-evaluate the safety and define the risk level of the engineered slopes. To define the slope stability of such a system, the phenomenon of soil-atmosphere interaction is necessary to be analyzed. The slope stability will be governed by a coupled system's thermal, hydro, and mechanical conditions. Moreover, the vegetation as a factor that has additional effects on rainfall infiltration water and evapotranspiration is not considered in this study. The paper presents an analysis of an ideal slope example subjected to intense rainfall, for which both physical and numerical models were employed. The aim was to assess the impact of infiltrated water on moisture and suction as the main factors that lead to instability. The sandy soil slope with an angle of 51 degrees is subjected to a rainfall intensity of 30mm/h until the failure occurs. The comparison of the experimental and numerical results has shown very good agreement. In conclusion, the results have shown that intensive rainfalls might have a significant impact on the surface layers of the slopes causing serious erosion and local instability which after a prolonged duration is transformed into a global slope failure mechanism.

RÉSUMÉ: L'article présenté contribue à la définition du comportement hydromécanique des sols non saturés tout en évaluant le problème des instabilités de pente induites par les précipitations. Les instabilités des pentes dans les pays des Balkans occidentaux, ont considérablement augmenté ces dernières années, en raison des effets du changement climatique et de son influence sur la stabilité des pentes. Outre le climat aride, les manifestations accrues de précipitations intenses, souvent égales à des précipitations mensuelles, sont considérées comme les principaux facteurs contributifs. C'est pourquoi, en Macédoine du Nord, une étude d'évaluation a été lancée dans le but de réévaluer la sécurité et de définir le niveau de risque des pentes aménagées. Pour définir la stabilité de pente d'un tel système, il est nécessaire d'analyser le phénomène d'interaction sol-atmosphère. La stabilité des pentes sera régie par les caractéristiques thermiques, hydroélectriques et mécaniques dans un système couplé. De plus, la végétation comme facteur ayant des effets supplémentaires sur l'eau d'infiltration des précipitations et l'évapotranspiration n'est pas prise en compte dans cette étude. L'article présente une analyse d'un exemple de pente idéale soumise à des précipitations intenses, pour lequel des modèles physiques et numériques ont été utilisés. L'objectif était d'évaluer l'impact de l'eau infiltrée sur l'humidité et la suction comme principaux facteurs conduisant à l'instabilité. La pente du sol sableux avec un angle de 51 degrés est soumise à une intensité de pluie de 30 mm/h jusqu'à ce que la rupture se produise. La comparaison des résultats expérimentaux et numériques a montré un très bon accord. En général, les résultats ont montré que les pluies intenses ont un impact significatif sur les couches superficielles des pentes, provoquant une grave érosion et une instabilité locale qui, après une durée prolongée, se transforme en un mécanisme global de rupture des pentes.

Keywords: Unsaturated soil; rainfall; slope stability; physical model; numerical model.

1 INTRODUCTION

The intense rainfalls due to climate variations and change are more often seen as a triggering factor for instabilities, such as soil sliding and erosion of natural and engineering slopes. This phenomenon widely

known as soil-atmospheric interaction is very often neglected by the engineers during the design. This interaction is realized through the wetting or drying of soil as a result of atmospheric, thermal, and hydraulic conditions. In the case of rainfall, the water infiltrates through the surface of the slope thus causing an

increase in the soil water content and pore pressure, while reducing the suction, thereby reducing the shear strength, and increasing the probability of sliding.

Figure 1 shows slope sliding and erosion that occurred on the Miladinovci – Shtip highway in the central part of Macedonia after heavy rainfall on 29 May 2022 (Susinov and Josifovski, 2022). The nearest weather station measured 52 and 43mm/h for two consecutive 12-hour periods. The national weather monitoring station measured 25.2mm in one hour and 40.1mm in two hours.



Figure 1. Erosion on the slopes between the 2 extreme rainfall events on May 29, 2022.

The rise in the soil water content significantly influences the behavior of soils to the extent that the classical theory of soil mechanics is no longer appropriate. Hence, to understand the behavior of unsaturated or partially saturated soils it is necessary to introduce additional parameters, dependencies, and theories. Moreover, for a comprehensive solution to the problem of rainfall-induced slope instabilities, coupled thermo-hydro-mechanical analyses need to be performed.

2 MATERIALS AND METHODS

To properly address the problem under consideration, it is necessary to use transient analysis which considers the mechanical and hydraulically soil models defining time-dependent material behavior. The most reliable and comprehensive method would be the so-called coupled flow-deformation analysis which is used in the present study. Successful application of this method requires knowledge of soil shear strength parameters, hydraulic parameters, and rainfall characteristics (Zhang et al., 2018). Then, not only the mechanical model but also the hydraulic model should be selected. It uses the relationship between soil suction and water content or saturation degree (S_r), the

so-called soil water retention curve – SWRC, and the suction-relative permeability relationship.

A sandy soil material was used in the present study (Susinov and Josifovski, 2018) defined with the Mohr-Coulomb model for the mechanical part ($\gamma=18.2\text{kN/m}^3$, $\phi=30^\circ$ and $c=0\text{kPa}$) and the user-defined (Spline) model for the hydraulic part. The SWRC and permeability function defining the relationship between the degree of saturation (S_r) – suction (ψ) and relative hydraulic conductivity (K_r) – suction (ψ) have to be determined with specific hydraulic laboratory testing.

A physical model representing an ideal slope subjected to intense rainfall with more than 30 mm/h intensity was adopted in this study (Susinov et al., 2019). An explanatory photo is shown in Figure 2. In particular, a large-scale model with the following dimensions $400 \times 200 \times 200$ cm was instrumented with three sensors (volumetric water content, pore water pressure, suction) on five different locations in the slope. Additionally, the deformations were scanned by LIDAR equipment and camera (Figure 3).

The aim was to assess the role of infiltrated water on moisture and suction through installed sensors as the main factors that lead to instability.



Figure 2. Photo of the physical model.

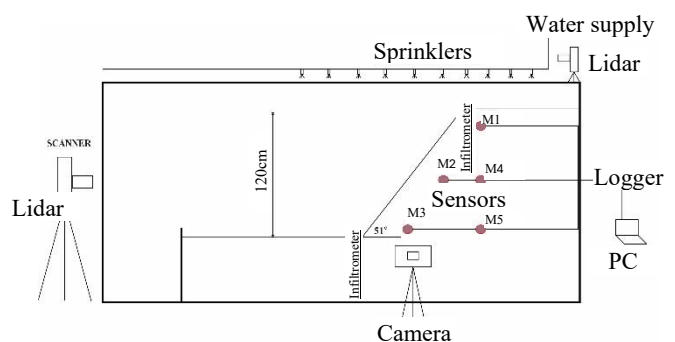


Figure 3. Schematic of the physical model and measuring sensors.

The change in volumetric water content (VWC) and suction during the rainfall event are presented in Figures 4 and 5, respectively.

Change in VWC was observed firstly at the M1 and M2 sensors placed near the slope surface. The value at the end of the test is lower in comparison with M3 and

M5 sensors which are placed near the phreatic level. It means that it is far from full saturation due to drainage of the infiltrated water into the lower layers. The lowest registered initial VWC is $0.050 \text{ m}^3/\text{m}^3$, while the highest at the end of the test is $0.422 \text{ m}^3/\text{m}^3$.

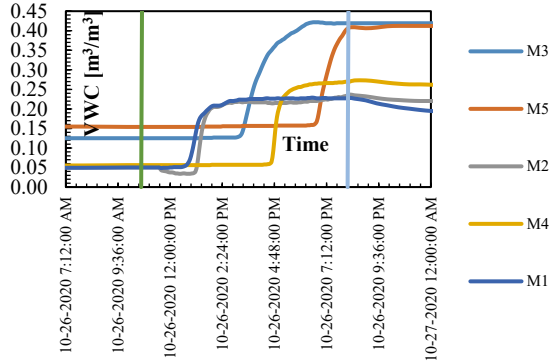


Figure 4. Changes in VWC during the rainfall event.

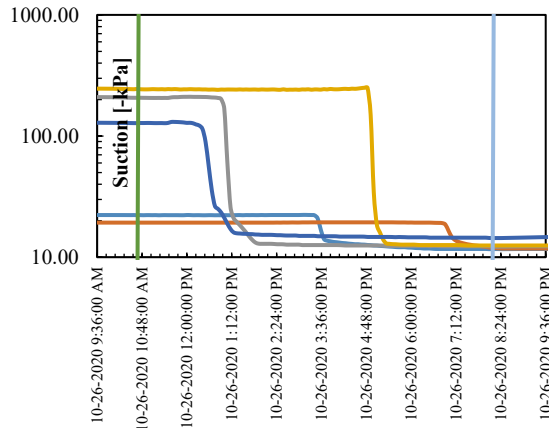


Figure 5. Changes in suction during the rainfall event.

The initial value of suction depends on the degree of saturation of the soil before the test. The sensors placed in the upper half of the slope (M1, M2, and M4) show the highest initial suction. A significant change – a drop in suction is observed when the infiltrated water reaches the sensor location. The largest registered initial suction is 244.7 kPa, while the lowest at the end of the test is 11.7 kPa. It can be concluded that the material loses suction relatively quickly during saturation.

3 NUMERICAL MODEL

Based on the data measured on the physical model during the rainfall test, a calibration of a numerical model subjected to constant rainfall was performed

using FEM analyses by way of the PLAXIS code. For simulation purposes, a fully coupled flow-deformation analysis was adopted using the relationships presented in Figure 6.

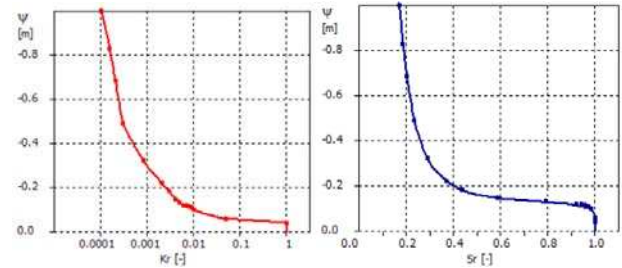


Figure 6. Used relationship for Spline model in PLAXIS.

In Figures 7 and 8 profiles of the saturation degree and suction before and after 3 hours of rainfall are respectively presented. The obtained results show a very good agreement with the measured ones.

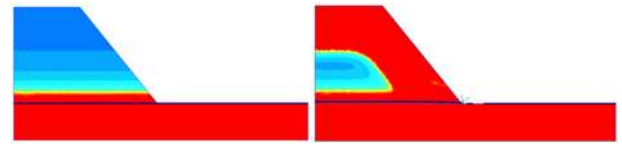


Figure 7. Degree of saturation before (left) and after (right) 3 hours of rainfall.

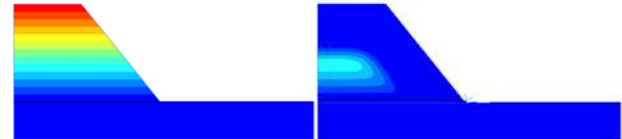


Figure 8. Suction before (left) and after (right) 3 rainfall.

The change in the saturation degree begins immediately after the beginning of rainfall as a result of the infiltration. In particular, the saturation zone increases and the suction decreases as the infiltration increases. The maximum saturation degree and suction changes were observed on the slope surface where the rainfall influence is the highest (Fredlund et al., 2012). The minimum value of the initial saturation degree at the top of the slope is 16.89%. As infiltration increases, the unsaturated zone decreases and matches that of the physical model. At the end of the test, the minimum value level of the saturation degree is 24.2%. The suction in PLAXIS is defined as negative pressure above the GWL and is related to the degree of saturation through the previously defined function which means that it cannot be compared directly.

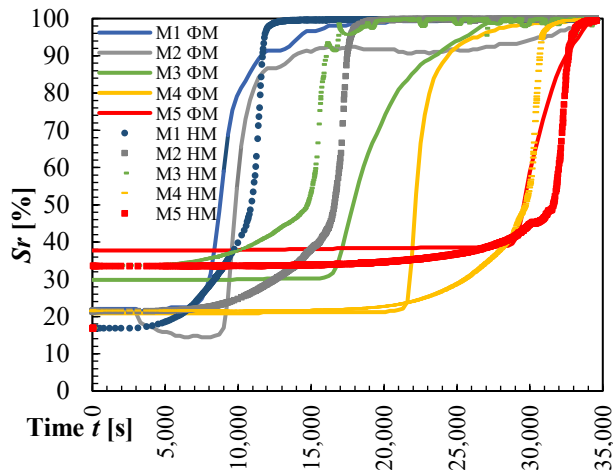


Figure 9. Comparison of S_r between the physical and numerical model.

Figure 9 presents the saturation degree value for both models. The initial degree of saturation in the characteristic points M1, M2, and M4 is lower compared to that in M3 and M5 where there is an influence from the groundwater due to the capillary effect. Compared over time, the degree of saturation at points M1 and M5 at the top of the slope and the lower part, respectively, show the best matching results. In points M2, M3, and M4, a minimal deviation is observed in the time when the change starts, although a sudden change is observed in both models. At the end of the analysis, all measuring points are completely saturated ($S_r=100\%$).

Another aspect of the comparison between both models is the deformations and the geometry of the potential failure surface. Thus, in Figure 10 the slope deformations with the ultimate global Factor of safety (FoS) are presented. The maximum calculated deformations are 6.62 cm and the minimum FoS equals 1.037, which is very close to the slope limit equilibrium.



Figure 10. Slope deformation in physical (left) and numerical (right) models.

4 CONCLUSIONS

Comparing the measured data from the test on the physical model and results obtained with numerical

analysis of slope stability, it can be concluded that there is very good agreement between them. In the initial phase of numerical analysis, the slope is partially saturated above the groundwater level, where the saturation is close to that in the physical model. From the influence of rainfall in the coupled analysis, the distribution of the degree of saturation and suction changes. The maximum suction occurs at the part above the groundwater level in the middle of the model, which is expected. Over time, maximum deformations develop in the lower part of the slope initiating its destabilization, as in the physical model.

If we compare the saturation degree value for both models, it can be concluded that the hydraulic behavior of the material in the physical model is similar to that of the numerical model.

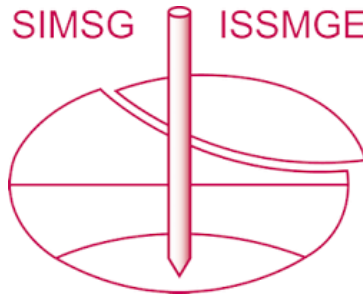
Regarding the deformations, it can be concluded that there is very good agreement with the measured and calculated displacement although the soil erosion cannot be simulated by FEM.

The forecasting of future climate change scenarios is challenging, thus the prediction of slope-atmosphere interaction effects represents a demanding engineering task. Nevertheless, the presented successfully tests a concept that can re-evaluate the stability and reliability of the existing slopes on prescribed rainfall intensities, which are expected to be even more frequent in the future, thus more slope instabilities are eminent.

REFERENCES

- Galavi, V. (2010). *Groundwater flow, fully coupled flow deformation and undrained analyses in PLAXIS 2D and 3D*, Plaxis report, [PLAXIS].
- Susinov, B. and Josifovski, J. (2018). Investigation of the hydro-mechanical properties of silty sand material from Topolnica tailings dam, In *ce/papers*, Skopje, R.N.Macedonia, pp. 797-802
- Susinov, B. Josifovski, J. and Naumovski, M. (2019). Hydrological analysis of high-intensity rainfalls over Topolnica tailing dam, In *Ss. Cyril and Methodius University, Civil Engineering Faculty – Skopje*, Skopje, R.N.Macedonia.
- Susinov, B. and Josifovski, J. (2022). Slope instabilities caused by atmospheric influences, In *Macedonian Association for Geotechnics*, Ohrid, N.Macedonia, pp. 669-678, ISBN 978-9989-2053-5-4
- Zhang, L., LI, J., Li, X., Zhang, J., Zhu, H. (2018). *Rainfall-induced soil slope failure: stability analysis and probabilistic assessment*, 1st ed., CRC Press, Boca Raton.

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