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EXPERIMENTAL AND NUMERICAL MODELING OF SOIL-VEGETATION-ATMOSPHERIC INTERACTION ON SLOPES AND EROSION CONTROL USING BIOPOLYMERS AND VEGETATION

JOSIF JOSIFOVSKI [1], BOJAN SUSINOV [2], ALEKSANDRA N. ATANASOVSKA [3]

[1] *Prof. Dr. University "Ss. Cyril and Methodius" in Skopje, Faculty of Civil Engineering, N. Macedonia, jjosifovski@gf.ukim.edu.mk*

[2] *Assist. Prof. Dr. University "Ss. Cyril and Methodius" in Skopje, Faculty of Civil Engineering, N. Macedonia, susinov@gf.ukim.edu.mk*

[2] *M.Sc. Skopje, N. Macedonia*

Abstract

The impact of climate change on the infrastructure creates serious challenges, especially affecting the stability and safety of the soil-cut slopes. The large temperature variations and more frequent intense rainfalls are the main contributing factors for soil instabilities, erosion, and landslides. This phenomenon is widely known as soil-atmospheric-vegetation interaction is studied. The hypothesis that intense rainfalls significantly impact slope stability has been investigated. Moreover, the application of biopolymers as a naturally-based solution and vegetation for erosion control has been tested. For this purpose, a holistic approach has been employed combining theoretical and experimental results.

The paper presents a unified methodology of physical and numerical modeling, laboratory and experimental tests, on soil slopes subjected to intense rainfalls with biopolymer-treated soil. The obtained results indicate that intense rainfalls significantly impact the stability of the surface layers where erosion occurs, leading to local instability which eventually can develop into a global failure and sliding. The results show that the biopolymer significantly reduces erosion and restricts the run-off water by infiltrating the ground, thus providing surface stability to the slopes and promoting vegetation growth. The tests confirm that the biopolymers significantly enhance the erosion resistance and stabilize the soil thus improving the slope stability.

Key words

Rainfall, Unsaturated soil, Erosion, Slope stability, Naturally-based solution, Biopolymer treatment.

1 Introduction

The influence of climate change in the infrastructure sector is becoming alarming and should not be ignored. Climate change creates several challenges for infrastructure projects regarding their lifespan and transport safety, especially on the soil-cut slopes. The high-temperature variations and intense rainfall are more often seen as triggering factors for instabilities, such as soil sliding and erosion of natural and engineering slopes. This soil-atmospheric-vegetation interaction phenomenon is neglected by engineers in the design process. The interaction is defined by soil wetting or drying due to the atmospheric, thermal, and hydraulic conditions.

Climate change can bring more frequent and intense rainfall that will cause increased soil water content in the surface layers. The soil water content is an important element for the soil stability but also for the vegetation dynamics largely depend on soil water availability, which, in turn, results from several complex and mutually interacting hydrologic processes (Chen et al. 2007). Different vegetation and soil types have different water infiltration capacities. Root systems make the soil more resistant to external influences. Figure 1 shows slope erosion and local sliding of soil slope 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 43 mm/h for two consecutive 12-hour periods. The national weather monitoring station measured 25.2 mm in one hour and 40.1 mm in 2 hours.

Figure 1. Slope exposed to intensive erosion on the Highway Miladinovci – Shtip, N. Macedonia.

To understand the unsaturated or partially saturated behavior of soils, it is necessary to introduce additional parameters, dependencies, and theories. Moreover, as a comprehensive solution of rainfall-induced slope instabilities, coupled hydro-mechanical analysis needs to be performed.

Natural soil improvement techniques can increase erosion resistance by improving mechanical and hydrological soil properties (Ham et al. 2018). Such is the biopolymeric material produced by microorganisms, algae, plants, etc., which is considered ecological and sustainable. In the past decade, natural polymers have been identified as highly effective polymers that stabilize soil surface structure and improve infiltration (Lentz et al. 1997). Natural polymers are water soluble and when mixed with soil, they can produce increased soil strength, improve cohesion, and reduce water permeability.

Figure 2 shows the erosion resistance model of polymer-treated soil. The gel-like structure of the polymer solution fills the pores and cavities, which reduces the potential for infiltration, and coats the grains, increasing the adhesion and strength (Ivanov et al. 2008). Soils treated with polymer solutions form a solid surface crust that prevents water infiltration and allows free surface runoff without soil erodibility (Cheng et al. 2015). Polymer-treated soils have an additional positive effect on vegetation, primarily due to the absorption and retention of moisture, which stimulates growth (Chung et al. 2018).

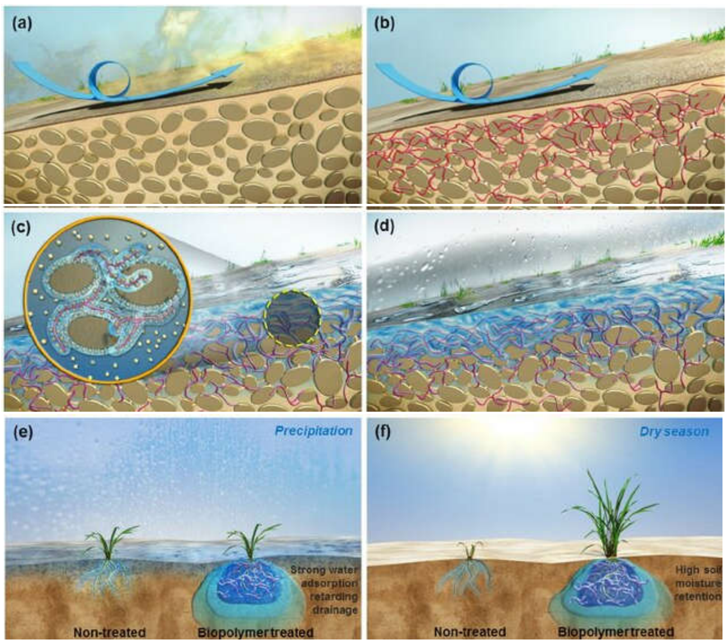

Figure 2. Erosion resistance model of biopolymer-treated soil.

In this study, a biopolymer binder is used as a naturally-based solution for erosion control. The effects are e examined through laboratory and experimental tests. Moreover, the physical and numerical modeling on an example of an ideal slope is employed to describe the complex interaction in the system between the hydraulic, thermal, and mechanical parts using an advanced fully coupled model.

2 Testing Methodology and Results

The testing methodology used in this study has been organized into three stages. In the first stage of the research, the material characteristics and biopolymer-treated soil characteristics are determined through laboratory tests. The biopolymer was applied in two concentrations of 1% and 2% mixed with the soil for a laboratory test and sprayed on the surface of the slopes in the experimental test. The composition and production details of the biopolymer can not be presented in this paper. In the second stage, several experimental tests were performed on a physical model for the untreated and biopolymer-treated slopes subjected to intense rainfall. The model was instrumented to measure several variables and soil characteristics during the testing. Finally, in the last research stage, employing all the previously gathered results a finite element numerical model was used to describe the complex soil-atmospheric-vegetation interaction.

2.1 Laboratory tests

In this study to determine the physical and mechanical properties of the soil around 60 laboratory tests have been performed. Figure 3 shows the grain size distribution curve of the soil of silty sand material that was tested.

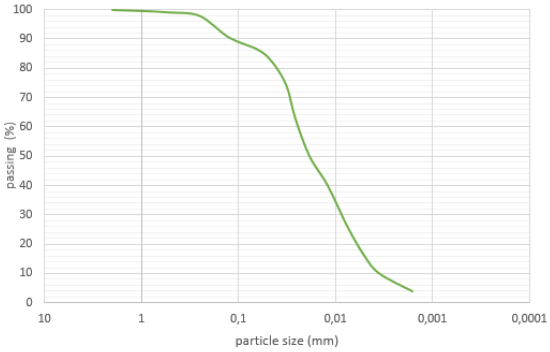

Figure 3. Grain size distribution curve.

The strength-deformation characteristics of the material were obtained through tests of Uniaxial Compressive Strength, Direct shear, Vane, and Oedometer tests. The water permeability has been determined for a pressure of 0.5 bar for saturated samples, Figure 4.

Figure 4. Soil samples from laboratory tests.

Table 1 presents the characteristic values of the material properties of silty sand soil.

Table 1. Physical properties of silty sand soil.

Natural moisture ω [%]	Unit weight γ [kN/m^3]	Specific gravity Gs [/]	Optimal moisture ω_{opt} [%]	Dry unit weight γ_d [kN/m^3]
23.62	18.82	2.67	17.60	15.20

The representative values of the resistance angle and cohesion have been determined as the average value of two series with three samples for untreated and biopolymer-treated soil. Table 2 presents the results of strength-deformation parameters, the angle of initial friction, and cohesion, where improvements of 9.52% and 7.5% are registered, respectively. The compressibility modulus is calculated for a normal stress of 240 kPa and represents an improvement of 36.64% compared with the modulus of untreated soil.

Table 2. Strength and deformation parameters.

Untreated soil			Polymer-treated soil		
ϕ [°]	c [kPa]	M_v [kPa]	ϕ [°]	c [kPa]	M_v [kPa]
29.2	25.9	4648	32.3	28.0	2945

The uniaxial compressive strength (UCS) was determined on samples with dimensions of 5.0 cm by 10.0 cm in series on 1, 7, 14, and 28 days. Tables 2 and 3, present the results of untreated and biopolymer-treated samples.

Table 3. UCS of untreated soil samples.

Day of Testing	Normal stress σ [kPa]	Strain ε [%]
1	435.3	4.0

Table 4. UCS of biopolymer-treated soil samples.

Day of Testing	Normal stress σ [kPa]	Strain ε [%]
1	257.1	3.5
7	1749.9	2.9
14	1132.4	2.6
28	2000.6	2.9

The volume of infiltrated water in the biopolymer-treated sample was 6.71 cm^3 /day, which is 6 times higher than the amount of the natural sample, 1.06 cm^3/day. Hence, biopolymer-treated soil has hydrophobic effects on the soil that allow free flow, unlike natural soil where the water is retained. Therefore, the water permeability coefficient tested for treated soil is 2.20 x 10^{-6} m/s and for the natural soil is 3.47 x 10^{-7} m/s.

2.2 Physical model test

The test has been performed on a large-scale physical model of an ideal slope subjected to intense rainfall with more than 30 mm/h (Susinov et al., 2019). An explanatory photo is shown in Figure 2. In particular, a large-scale model with the following dimensions 400 × 200 × 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 5.

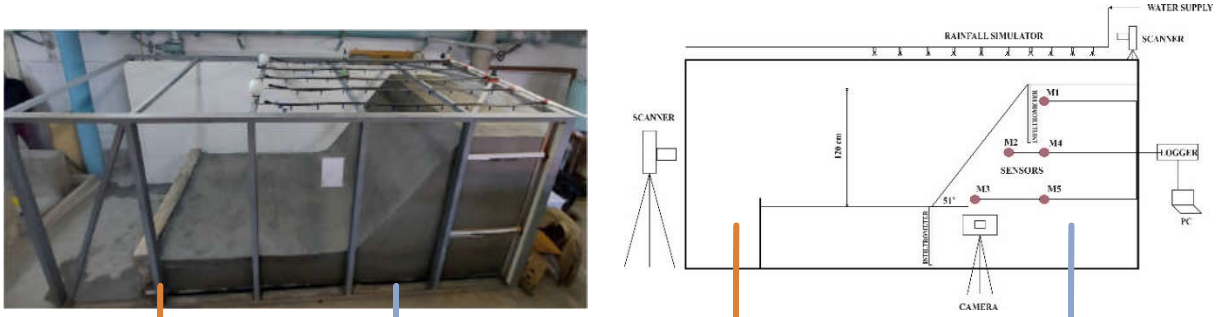

Figure 5. Photo of the physical model and schematic of the measuring equipment and sensors.

In the present study, a selected sandy soil material (Susinov and Josifovski, 2018) has been used with the following mechanical characteristics, unit weight γ=18.2kN/m^3, resistance angle φ=30˚, and cohesion c=0 kPa. The hydraulic characteristics have been defined through the SWRC and permeability function obtained by specific hydraulic laboratory tests giving a relationship between the degree of saturation (S$_r$) – suction (ψ) and relative hydraulic conductivity (K$_r$) – suction (ψ). The results of the volumetric water content (VWC) and suction during the test are presented in Figure 6, respectively.

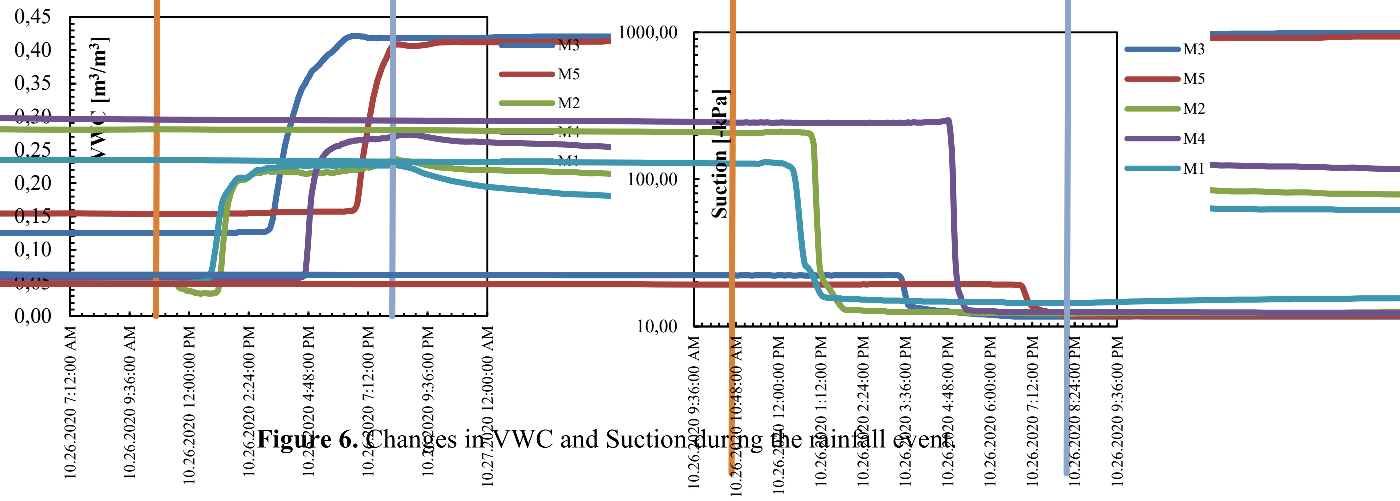

Figure 6. Changes in VWC and Suction during the rainfall event.

A change in VWC has been initially observed at the M1 and M2 sensors placed near the slope surface. Later they have lower values compared to those of the M3 and M5 sensors, which are placed near the phreatic level. The suction strongly depends on the VWC, thus the sensors placed in the upper half of the slope (M1, M2, and M4) show the highest initial suction. A significant drop in suction is observed when the infiltrated water reaches the sensor location.

2.3 Erosion resistance test

In the second stage of this study, an experimental test for erosion control on an inclined slope of biopolymer-treated and untreated soil slope was performed in an aluminum box with the following dimensions 50 × 50 × 10 cm, Figure 7. The rainfall was simulated through a system of sprinklers which were installed above the model and connected to the water supply system. Inside the box, the soil was instrumented with three types of sensors for volumetric water content, pore water pressure, and suction.

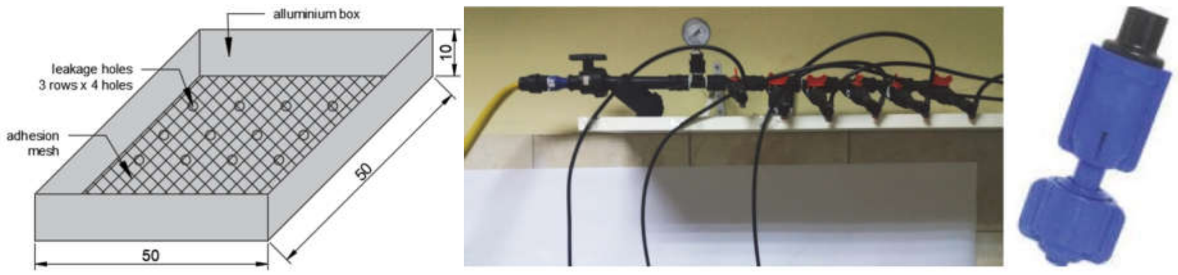

Figure 7. Test box and the sprinkler system.

The biopolymer solution has been applied by spraying evenly over the slope surface filling the pores and cavities in the soil and coating the grains with a biofilm creating a surface crust. The rainfall duration was 180 minutes, while every 60 minutes snapshots were made to register the changes on the surface of the slopes. In the beginning, there was no visual difference between the treated and untreated slope. The interaction between the biopolymer solution, soil, and water creates a specific soil rheology characterized by hydrophilic absorption, and binding of water molecules. In contact with water, the surface crust becomes a hydrophobic surface that allows surface water to flow freely with high resistance against the erosive forces of water visible in Figure 5 where practically no erosive changes were observed on the polymer-treated slope in 180 minutes (Nikolovska et al. 2022). After the soil was completely saturated, the water started to drain through the boreholes at the base, and movement paths of the eroded soil were observed on the surface. After 180 minutes, there was muddy water with fine fractions in the base of the slope, which was not the case with the treated slope. The erosion effects on a polymer-treated and untreated slope with an inclination of 1:1 is shown in Figure 8.

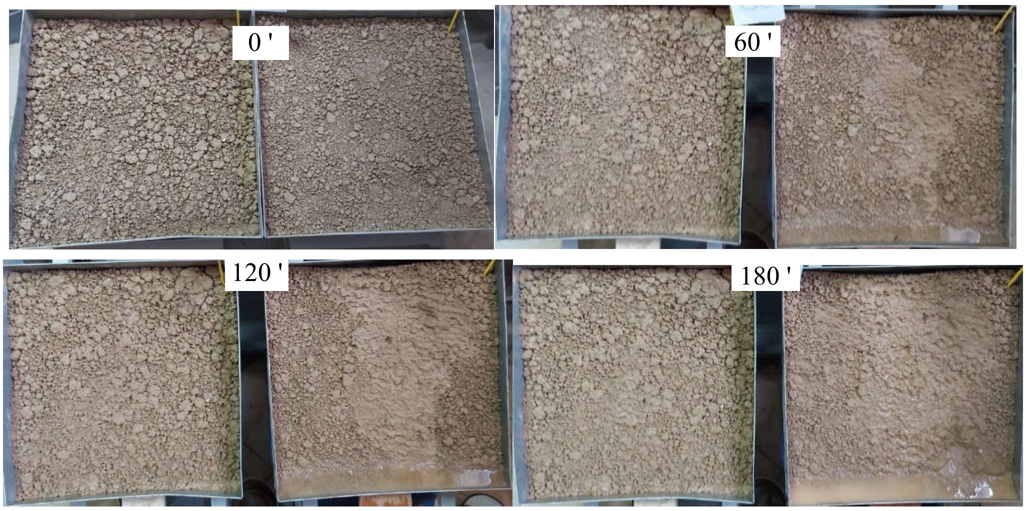

Figure 8. Erosion on polymer-treated slope (left side) and untreated slope (right side).

A series of tests on untreated and biopolymer-treated slopes with grown vegetation were also tested on 120 minutes of rainfall with an intensity of 12 l/h. During the rainfall, no erosion was observed, hence, the biopolymer-treated slope has a higher stability and resistance to erosive forces (Nikolovska et al. 2023). For precipitation duration of 3 h on an area of 1.0 m^2, a material with a weight of 1900 gr is eroded, which represents a loss of material of 9.5%, Figure 9.

Figure 9. Eroded soil in 180 minutes of rainfall for polymer-improved slope (left side) and natural slope (right side).

Moreover, the absorption capability of the biopolymer supports and stimulates vegetation growth. The biopolymer-treated slopes with vegetation were tested after 27 days of curing period. The curing period is needed for the vegetation roots to connect with the soil and hydrophobic layer, Figure 10.

Figure 10. Erosive changes of slopes with vegetation, polymer-improved slope (left side), and natural slope (right side)

Figure 11 presents the measured VWC and suction during the test on the inclined slope subjected to rainfall.

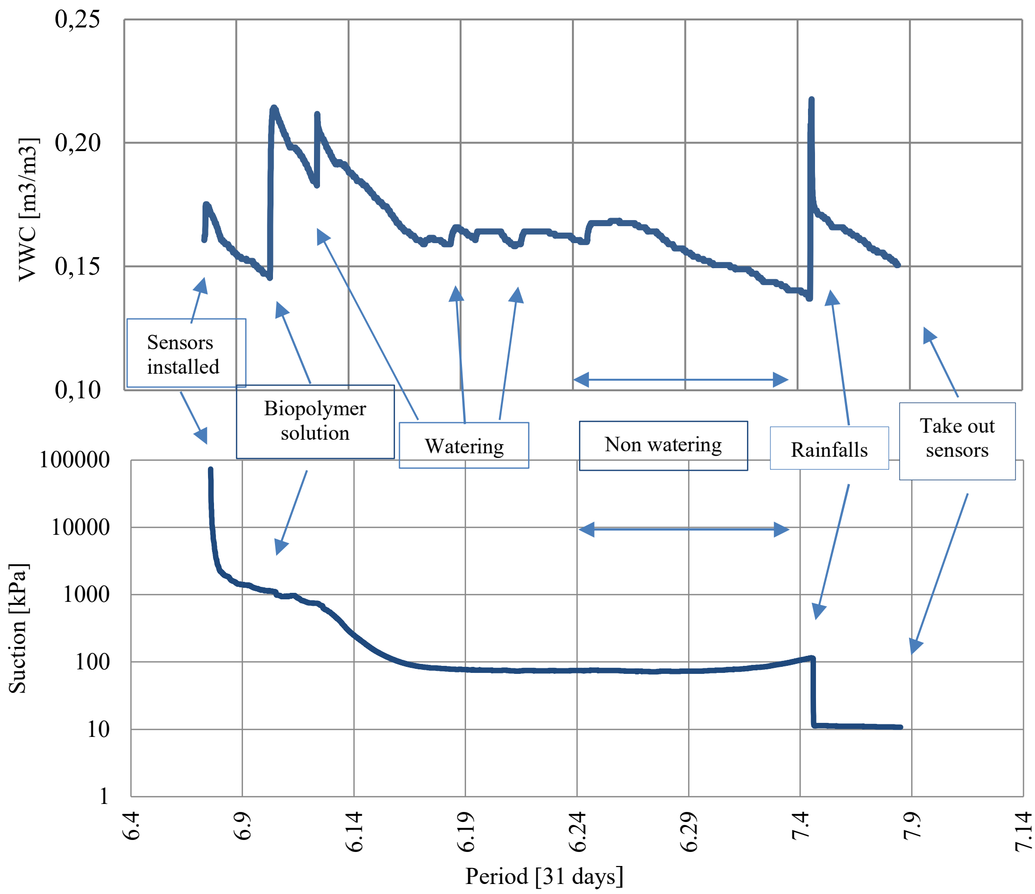

Figure 11. Results of Volumetric water content and suction for silty sand soil

During the wetting period, the volumetric soil moisture increases from 0.137 m^3/m^3 to 0.218 m^3/m^3, while in the dry periods decreases while the suction sharply decreases from 110.1 kPa to 11.3 kPa or reduces by almost 90%.

2.4 Numerical test

To simulate the soil-atmospheric-vegetation interaction, it is necessary to use unsaturated soil mechanics with a definition of constitutive both mechanical and hydraulic soil models. The most reliable and comprehensive solution would be to perform a transient analysis with the coupled flow-deformation calculation. A small-strain hardening soil model was used in definition of the mechanical behavior, and van Genuchten model for hydraulic. For the definition of the hydraulic model, the soil water retention curve – SWRC, and the suction-relative permeability function are both presented in Figure 12.

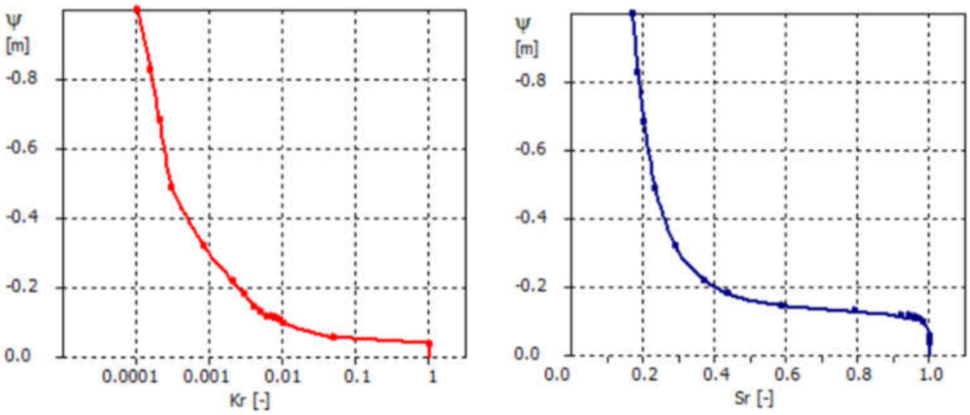

Figure 12. Used relationship for Spline model in Plaxis.

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 using the Plaxis software. Figures 13 and 14 present the results of the saturation and suction profiles before and after 3 hours of rainfall, respectively.

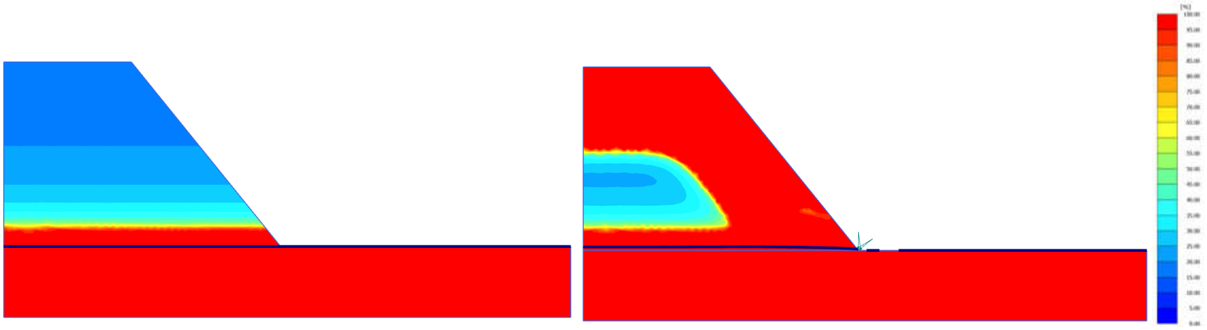

Figure 13. Degree of saturation before (left) and after (right) 3 hours of rainfall.

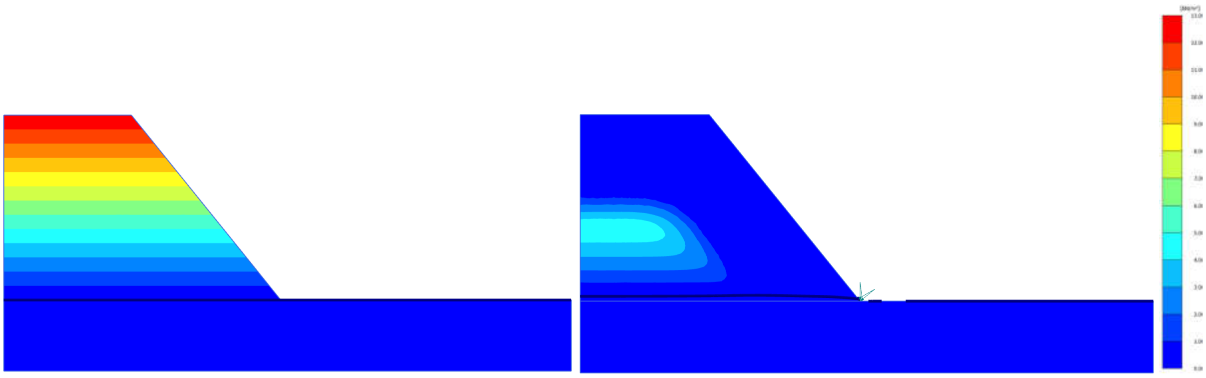

Figure 14. Suction before (left) and after (right) 3h rainfall.

The saturation changes immediately after the beginning of rainfall because of the infiltration. With time the saturation zone increases and the suction decreases as the infiltration increases. The maximum saturation 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 those of the physical model. At the end of the test, the minimum value level of the saturation degree is 24.2%. The calculated results show exceptional agreement with the measured ones, see Figure 15.

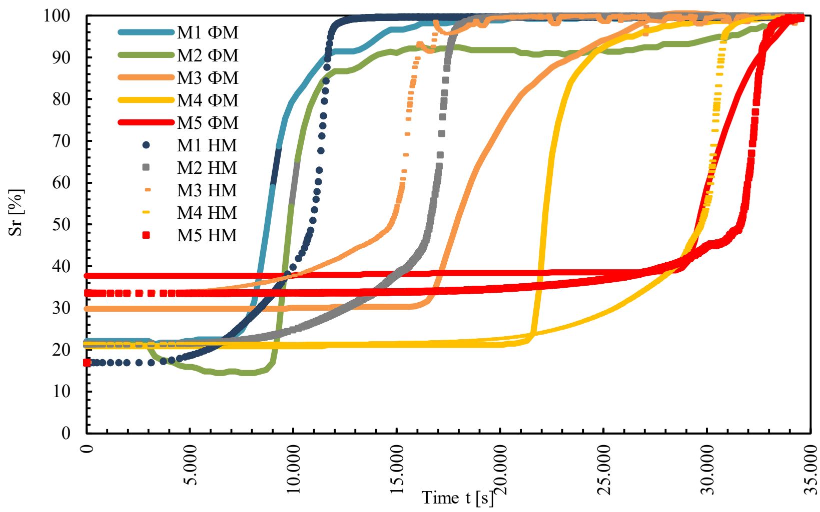

Figure 15. Comparison of S_r between the physical and numerical model.

The initial degree of saturation in the characteristic points M1, M2, and M4 is lower if compared to M3 and M5 due to the influence of the capillary effect. The saturation at points M1 and M5 at the top of the slope and the lower part compared over time show excellent matching. In points M2, M3, and M4, a minimal deviation in the results can be observed. A comparison between both models is also made regarding the deformations and the geometry of the potential failure surface. Hence, in Figure 16 the slope deformations with the ultimate global Factor of safety (FoS) are presented. The maximum calculated deformations are 6.62 cm and the minimum global FoS equals 1.037, which is very close to the slope limit equilibrium.

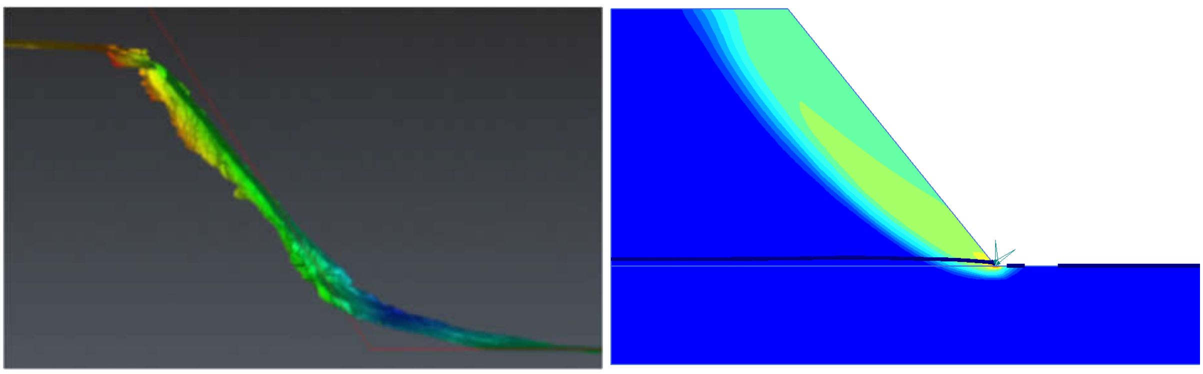

Figure 16. Slope deformation in physical (left) and numerical (right) models.

4 Conclusion

Nowadays, the consequences of climate change are becoming more visible, among other, it has a great impact on the stability of soil slopes. The increased precipitation and dry periods affect slopes and their stability causing erosion, development of cracks, and shallow (local) and even global instabilities and landslides. As a preventive measure, more recently, the use of natural microorganisms for soil improvement has attracted the attention of researchers. This research examines the stabilization with the natural polymer solution that forms a viscous gel matrix strengthening the bond between the soil particles. The results show that the polymer significantly reduces erosion and restricts the runoff water by infiltrating the ground, thus providing surface stability to the slopes and promoting vegetation growth. The laboratory tests have shown not just an increase in the cohesion of the treated soil, but also in the friction angle and modulus of compressibility by 20% to 50%. It is evident that biopolymers as an efficient, economical, and environmentally sustainable solution have great application potential.

Moreover, the study quantitatively evaluates the impact of precipitation intensity, frequency, and duration on slope stability. The obtained results from both physical and numerical modeling show that the intense short-term rainfall has significantly affected the stability of the slopes, caused erosion and reducing the slope stability by 30%. The results show that the biopolymer significantly reduces erosion and restricts the run-off water by infiltrating the ground, thus providing surface stability to the slopes and promoting vegetation growth. The tests confirm that the biopolymers significantly enhance the erosion resistance and stabilize soil thus improving the slope stability. The biopolymers stimulate the growth of the vegetation has additional beneficial effects. The study also highlights the importance of stability checks considering intense rainfall with short to medium duration recommending a probabilistic analysis to assess the risk of instabilities for projected rainfall intensities.

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