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Experimental and numerical investigation of the different root analogue systems effect on the soil strength and slope stability

Etude expérimentale et numérique de l'effet des différents systèmes analogues racinaires sur la résistance du sol et la stabilité des pentes

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ABSTRACT: Vegetation contributes to slope stabilisation in two ways, mechanical and hydrological. This paper investigates plant reinforcement to the stability of medium-grained slopes by exploring the relative contribution of mechanical and hydrological effect of different root analogue systems. To achieve this aim, firstly, the impact of root area ratio (RAR) and root architectural design (unbranched and branched roots) on the soil strength is studied for cohesionless soil using direct shear test apparatus. Secondly, a combined hydrology and stability model (CHASM) is used to evaluate the factor of safety of three different slope geometries reinforced with several root mechanical parameters. A 3D printing method was used to develop different tap root analogue systems that simulate willow live poles' development during their growth stages. Results showed that the RAR has a significant impact on soil shear strength, followed by root morphology. The presence of branches increased the deformation needed to achieve peak shear strength which increased soil shear resistance. For the type of the roots, soil and slope geometries employed in this study, it is shown that the magnitude effect of the mechanical properties of roots is higher than the hydrological effect, which helped to keep the slope stable during the rainfall period.

RÉSUMÉ : La végétation contribue à la stabilisation des pentes de deux manières, mécanique et hydrologique. Cet article ét udie le renforcement des plantes à la stabilité des pentes à grain moyen en explorant la contribution relative de l'effet méc an ique et hydrologique de différents systèmes analogues de racines. Pour atteindre cet objectif, tout d'abord, l'impact du rappor t de surface racinaire (RAR) et de la conception architecturale des racines (racines non ramifiées et ramifiées) sur la résistan ce du sol est étudié pour un sol sans cohésion à l'aide d'un appareil d'essai de cisaillement direct. Deuxièmement, un modèle combiné d'hydrologie et de stabilité (CHASM) est utilisé pour évaluer le facteur de sécurité de trois géométries de pente di fférentes renforcées par plusieurs paramètres mécaniques de racine. Une méthode d'impression 3D a été utilisée pour dévelop per différents systèmes analogiques de racine pivotante qui simulent le développement des poteaux de saule au cours de leur s stades de croissance. Les résultats ont montré que le RAR à un impact significatif sur la résistance au cisaillement du sol, suivi par la morphologie des racines. La présence de branches augmentait la déformation nécessaire pour atteindre une résist ance maximale au cisaillement, ce qui augmentait la résistance au cisaillement du sol. Pour le type de racines, les géométrie s de sol et de pente utilisées dans cette étude, il est montré que l'effet de magnitude des propriétés mécaniques des racines e st plus élevé que l'effet hydrologique, ce qui a contribué à maintenir la pente stable pendant la période des pluies.

KEYWORDS: Analogue root models, Vegetation, Root area ratio, Root reinforcement, Slope stability, CHASM

1 INTRODUCTION

Stabilising slopes using plant roots have been considered an environmentally friendly and cost-effective engineering method. Rainfall events are considered one of the main factors of slope failure by causing more rainwater to infiltrate into the slope and increase pore-water pressure. Vegetation can significantly impact geotechnical parameters of soil and, as a result, slope stability. The mechanical effect of roots is provided by the mechanical interaction between roots and the host soil. The hydrological impact that contributed to plant evapotranspiration increases the soil matric suction (Coppin & Richards, 1991; Waldron & Dakessian, 1982). Such effects depend on root system development, which influences the spread and the root area ratio (RAR: percentage of the cross-sectional area of roots which penetrate the shear plane to the area of the shear plane. Root reinforcement efficiency is affected by RAR, root tensile strength, root distribution and orientation, root length and density (Mao et al., 2014; Vergani et al., 2014).

The mechanical and hydrological effect of vegetation has been subjected to some debate. Some studies concluded that the direct reinforcement available from roots is identified to provide one of the most significant contributions to slope stability (Eab et al., 2015). Root architecture has an important contribution to the mechanical behaviour of soil permeated with roots. Mickovski et al., (2009) found a strong relationship between RAR and shear strength increment of planted slopes. Additionally, root branching was found to play an important role in increasing the shear resistance and protecting slopes from shear failure. In this paper, RAR and root branching will be the main parameters of interest regarding the mechanical properties of roots. Moreover, the efficiency of the mechanical effect of roots will be discussed as a correlation to soil properties.

The hydrological influence of roots was found to be minimal during rainfall as the evapotranspiration effect of roots will be minimal (Feng et al., 2019). However, this effect found to be dominant during the dry periods. The hydrology of different cohesionless and high permeable slope geometries will be investigated in this study using a combined hydrology and stability model that will be examined for simulation periods before, during, and after 24h rainfall storm.

This paper outlines the relative importance of the hydrological and mechanical effect of different root analogue systems on shear strength and slope stability. The relative impact of RAR and root morphology on soil shear resistance will be evaluated. Which will enable the relationship between shear strength increment, different RAR values, and root morphologies to be determined. The studied root properties were chosen to represent different growth stages of live willow poles.

2 MATERIALS AND METHODS

2.1 *Root model fabrication and mechanical properties*

This study will investigate the influence of roots on soil strength and slope stabilisation. Using real plant roots is time-consuming, and it is also challenging to come with repeatable root systems because of the complexity and the significant factors which affect root growth. Ultimaker[GB] 3D printer was used to produce the printed roots. The material used in the printing process is acrylonitrile butadiene styrene (ABS) plastic, which is expected to come with printed roots with similar mechanical properties to real roots (Huat & Kazemian, 2010; Liang et al., 2017; Norris et al., 2008).

The printed root models were chosen to simulate the shape and architectural design of live poles. Figure 1 shows examples of young willow which have been grown from live poles.

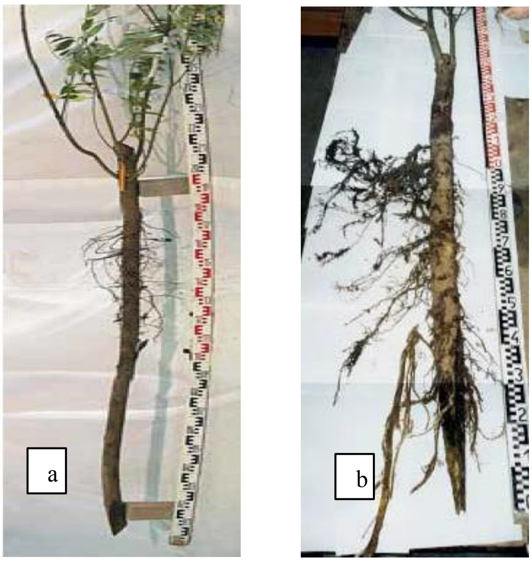
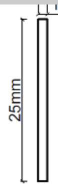
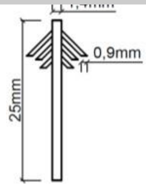
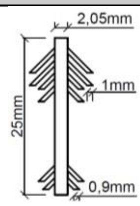
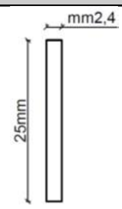


Figure 1: Willow poles roots, a) 2.5 years old, b) 3.5 years old (Steele et al., 2004)

The root models were designed to realistically represent the geometry, spatial distribution and RAR of unbranched poles and branched young willow trees. To get the best results from using the direct shear test for reinforced samples, the finest root diameter should not be relatively smaller than D_{50} (the diameter of particles which 50% of soil particles are smaller than, for the studied Leighton buzzard sand, D_{50} was equal to 0.88). Therefore, the min root diameter was chosen to be 0.9mm. Furthermore, the root analogues were designed to get the required RAR of willow poles and young willow trees (0.006 and 0.02, respectively) with 25mm root depth which will enable the roots to cross the shear plane of the direct shear test box. Table 1 shows all designs dimensions of root analogues with their geometrical properties. The taproot part, as well as all lateral branches, were all cylindrical. Constraints related to shear box dimensions prevented the design of more complex root analogue systems.

Table 1: Root analogues properties, Ri: root name, N: number of roots in the shear box, RAR: the percentage of the cross-sectional area of root analogues which penetrate the shear plane to the area of the shear plane.

Root morphology		
Root properties	R1, N= 16, RAR= 0.006	R2, N= 16, RAR= 0.006
Root morphology		
Root properties	R3, N= 16, RAR= 0.02	R4, N= 16, RAR= 0.02

2.2 *Test procedure*

Direct shear tests were performed on rooted and bare soil using a conventional shear box (60mmx60mmx35mm). Medium Leighton buzzard sand fraction B (LBS) was used to perform the direct shear tests in this study. The minimum and maximum void ratio were found to be 0.55 and 0.88, respectively. The same void ratio (e) and the relative density (D_r) of 0.72 and 40%, respectively, were used for all tests. The root models (16 roots) were inserted in the direct shear box which was initially filled with LBS (Figure 2) to study how the change in root properties will affect the shear strength of the soil.

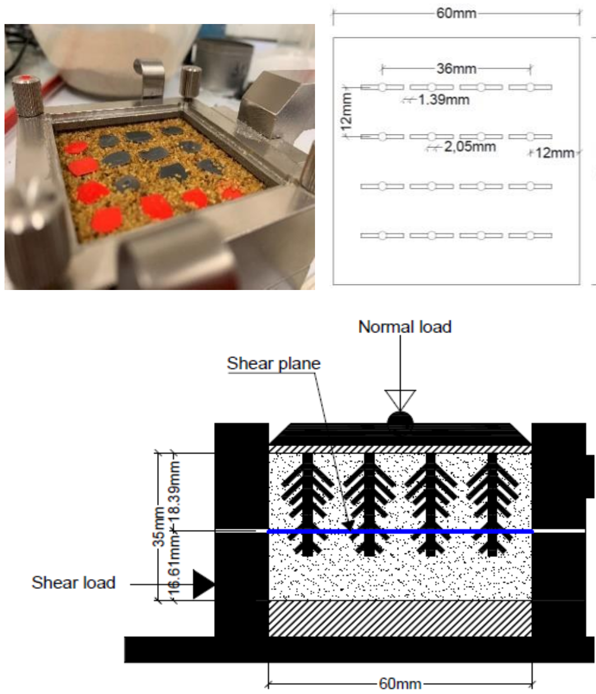


Figure 2: Root (R3) distribution in the shear box

2.3 *Slope combined hydrology and stability modelling*

The combined hydrology and stability model (CHASM) was used to investigate the mechanical and hydrological effect of roots on the stability of different slope geometries (Wilkinson et al., 2002). CHASM is a physically-based combined soil hydrology-slope stability model that simulates the impact of rainfall on slope stability by measuring the change in pore water pressure and using the limit equilibrium stability analysis method. The slope cross-section was divided into a series of rectangular columns with a 0.5m width. Each column was subdivided into regular cells with dimensions of 0.5m x 0.5m, each cell with specific mechanical and hydrological properties (see Figure 3). In this study, the stability of bare and planted slopes with live poles and young willow will be studied to investigate the hydrological and mechanical effect of both vegetation types on the stability of different slope geometries.

Figure 3 illustrates how the slope is represented in CHASM and indicates the parameters required for the simulation.

The geotechnical parameters that have been used for CHASM simulations were obtained from experimental tests and Highways England and British geological survey (BGS) database (Table 2). The slope geometry and the hydraulic conductivity values of the soil were attained from a survey done by Perry (1989) for 750 km highway slopes in England & Wales and from the Highways England database. Root depth and spacing were obtained from field studies conducted by Steele et al. (2004) and Coppin & Richards (1991). Finally, the root tensile strength and root area ratio values were defined according to studies on young willow roots by Mickovski et al. (2009) and Sonnenberg et al. (2010). According to these studies, the root tensile strength value was between 2 MPa and 100 MPa, with most values between 10 MPa and 50 MPa. All parameters are shown in Table 2.

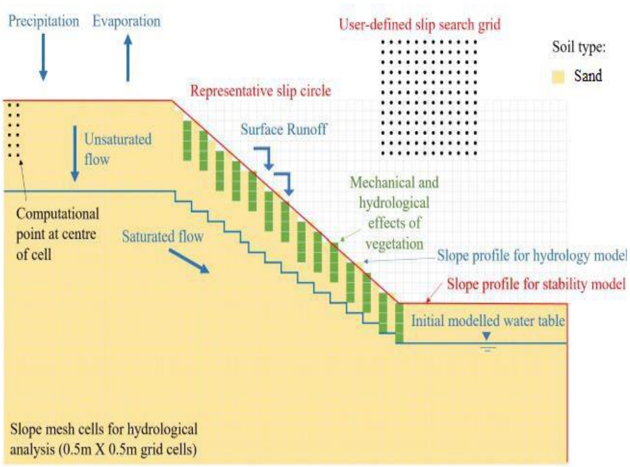


Figure 3: Representation of how slope is modelled in CHASM with the required parameters.

The initial water table (50% of the slope depth) was defined according to Steele et al. (2004). The simulation period was set to be 15 days, seven days of a dry period which was implemented to allow the initial groundwater table to reach the steady-state, then one-day rainfall storm was applied, and it was followed by another dry period of seven days.

In CHASM, the hydrology of the slope is modelled by a forward explicit finite-difference scheme which will allow the modelling of saturated and unsaturated flow using Darcy's law and Richards' equation (Darcy, 1856; Richards, 1931). The cell moisture content and pore water pressure are updated every time step (5 seconds). Rainfall is allowed to infiltrate into the slope and is governed by the infiltration capacity defined by the slope materials. The unsaturated conductivity is determined by the Millington Quirk Equation (Millington, 1959). Bishop's circular limit equilibrium method is used to assess the stability of the slope at the end of each hour. The vegetation was positioned on the slope with 1m intervals (see Figure 3) and with properties, as shown in Table 2.

Table 2: CHASM model input parameters

Parameter	symbol	Unit	value
Effective friction angle	Φ'	degree	37
Effective cohesion	C'	KPa	0
Unite weight	$\gamma_{usat}/\gamma'_{sat}$	KN/m³	17/20
Hydraulic conductivity	Ks	m/s	10^{-5}; 10^{-7}; 10^{-9}
Saturated moisture content	Θs	m³/m³	0.5
Slope height	H	m	5; 8; 10
Slope angle	α	degree	18; 26; 33
Root area ratio	RAR	m²/m²	0.006; 0.02
Root depth	Rd	m	1.5; 4
Root tensile strength	tr	MPa	10; 50
Surcharge	Sw	KPa	2

3 RESULTS AND DISCUSSION

3.1 *Direct shear test results*

All types of root analogues increased the peak shear strength of LB samples depending on root shape and RAR. Figure 4 shows the measured peak shear strength for bare and rooted samples; it should be noted that adding roots with the same RAR and different design gives different values for shear strength. For example, R3 and R4 root types have the same value for the RAR. However, R4 gave higher results for shear strength parameters. Root area ratio for R3 type of roots consists of thinner roots with more branches penetrating the shear plane than R4. The presence of root branches has an important influence on the soil shear strength. To reach the same value of shear displacement, more shear strength resistance must be overcome in the case of branched roots (see Figure 5), and this will result in higher deformation of branched roots and reduction of root slippage. Branched roots started to mobilise their additional shear strength at a higher shear deformation values which resulted in higher values for peak shear strength. For the same RAR value, the higher and thinner the roots will result in better improvement for the soil strength.

It has been noted also that the contribution of plant roots to the shear strength of soil may not be limited to the roots crossing the shear plane. For example, R2 roots type gave higher results for shear strength values than R1 although both of the roots do not have lateral branches penetrating the shear plane. The effect of this type of laterals needs to be studied more in the future tests using a large version of the direct shear test box and more complex root analogue systems. None of the tested roots broke during the shearing process.

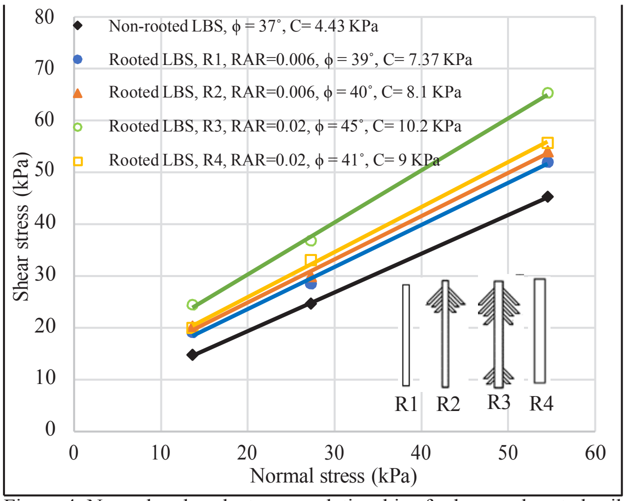


Figure 4: Normal and peak stresses relationships for bare and rooted soil with different root designs

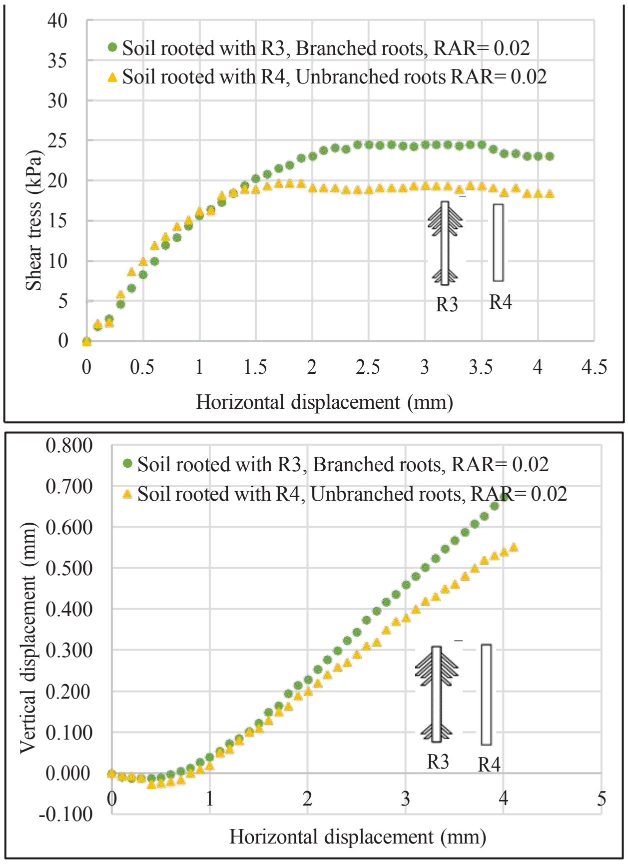


Figure 5: Influence of branching on the shear displacement. σ_n=13.26KPa

3.2 *CHASM modelling results*

The change in factor of safety has been investigated for bare and planted slopes over the simulation period (360h or 15days). The soil mechanical parameters resulted from the direct shear tests were used as inputs for CHASM simulations. Both willow poles and young willow trees improved the stability of the slopes. Bare and planted slopes with live willow poles have almost the same FOS up to the point before rainfall event begins (at t=168h or the seventh day of simulation) (see Figure 6). However, willow poles helped to increase slope stability during the rainfall event with a FOS value of 1.88, while this value was just 1.26 for the bare slope. On the other hand, young willow trees helped to increase FOS before and after rainfall with a minimum FOS value of 2.56 during a rainfall event.

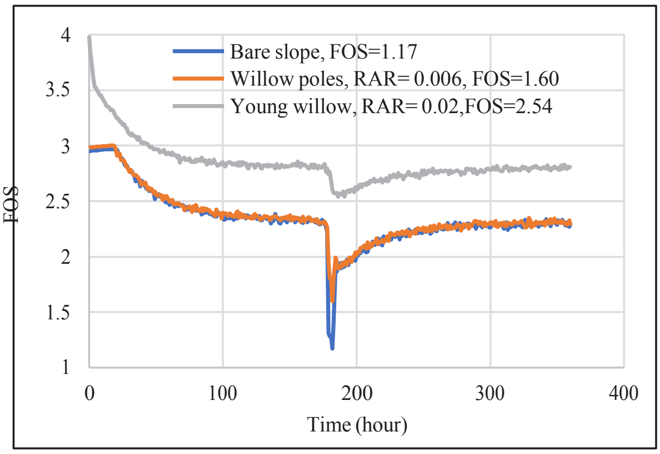


Figure 6: Comparison of slope response to different vegetation mechanical properties and 1day rainfall storm, slope gradient=18°, slope height= 5m, K=10^{-5} m/s

Pore-water pressure change with depth was used to investigate the relative importance of vegetation impact on the factor of safety results. Pore-water pressure developments for bare and planted slopes with willow poles were the almost same during rainfall event (see Figure 7), which means that the improvement of the FOS can be attributed to the mechanical effect of the roots. On the other hand, the pore-water pressure for slopes planted with young willow trees was higher than bare slopes during rainfall. This means that the roots of young willow trees enabled more water to infiltrate into the slope. However, the factor of safety for this kind of vegetated slopes is still higher (2.54) than bare slopes (1.17), even if the excess pore-water pressure is high. This explains the higher importance of vegetation's mechanical effect, which helped to increase the slope stability during the rainfall event. These results demonstrate the more significant influence of the mechanical impact of these types of roots than the hydrological effect on this kind of slope geometries and soil type, especially during rainfall events, which are considered a main cause of landslides.

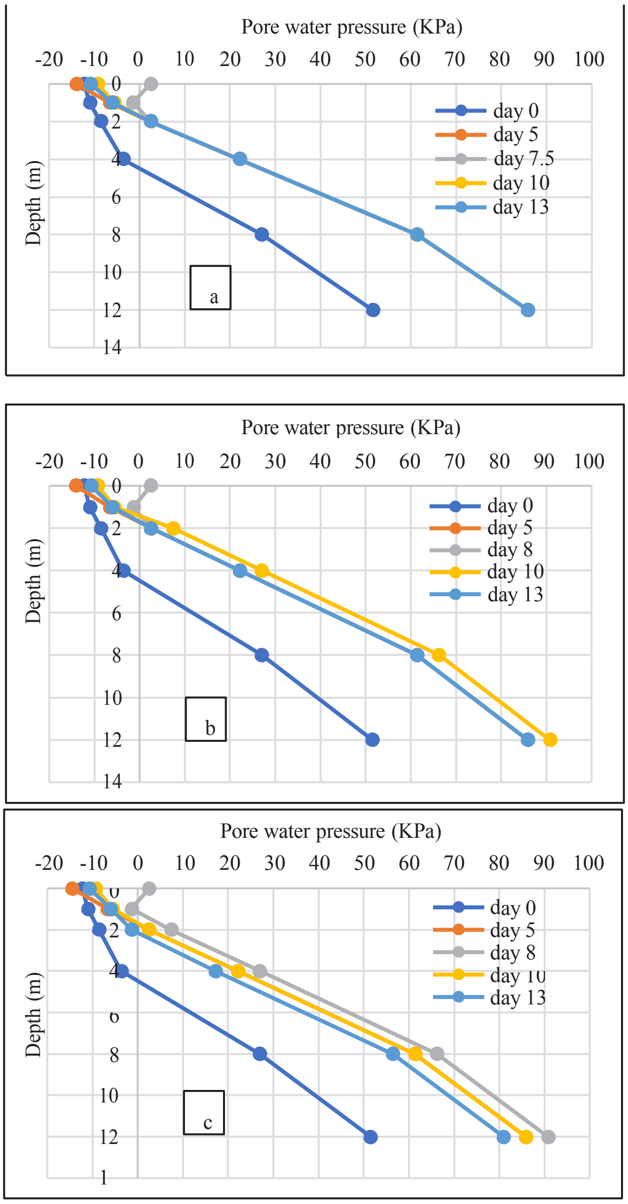


Figure 7: Pore water pressure change with depth during the simulation period. 24h rainfall event starts at 168 h, slope gradient slope gradient=18°, K=10^{-5}m/s. (a): bare slope, (b): planted live willow poles, (c): planted with young willow tree.

4 CONCLUSION

This paper explores the plant reinforcement impact on the stability of medium-grained slopes by considering the combined mechanical and hydrological effects of different root analogue systems. To achieve this aim, firstly, the influence of root area ratio (RAR) and root architectural design (unbranched and branched roots) on the soil strength was examined for cohesionless soil using direct shear test apparatus. Secondly, a combined hydrology and stability model (CHASM) was used to evaluate the factor of safety of three different slope geometries reinforced with several root mechanical parameters.

Direct shear tests on rooted samples showed that root area ratio has a significant impact on shear strength resistance followed by root morphology. Roots with branches mobilised their additional shear strength at a shear deformation higher than unbranched roots, which helped to improve the shear strength of soil by allowing more shear resistance to be achieved for the same shear displacement. The better improvement of branched roots is related to the additional reinforcement and shear resistance which root branches have added.

According to the hydrological modelling results, the excess pore-water pressure for planted slopes was almost the same or higher during rainfall; however, the FOS was higher than for bare slopes. As a result, the improvement in the factor of safety can be attributed to the mechanical effect of root reinforcement. So, it is demonstrated that the stability of this kind of cohesionless high permeable slopes is governed mainly by the mechanical impact of the considered type of roots. As the contribution of roots to slope stability is attributed to its mechanical effect, more studies should be conducted to investigate the effect of more complex root morphology on slope stability.

Future experiments using a large direct shear test are planned to be done. This will be in parallel with more CHASM simulations for a wide range of slope geometries to compare the relative importance of the mechanical and hydrological effect of vegetation on slope stability.

5 ACKNOWLEDGMENT

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