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Hydro-mechanical characterization of root–reinforced pyroclastic soils

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ABSTRACT: Rainfall-induced landslides in unsaturated pyroclastic soils are often triggered by reductions in matric suction and the resulting loss in shear strength due to rainfall infiltration. Despite the well-documented role of vegetation in slope stabilisation, the hydro-mechanical effect of plant roots on soil behaviour under unsaturated conditions remains poorly quantified, especially for pyroclastic soils. To fill this gap, an ongoing experimental study investigates the influence of root volume ratio (RVR) on soil strength under stress paths representative of critical in-situ conditions along potential slip surfaces. Reconstituted samples of pyroclastic soil from Lattari Mts. (Campania Region, Southern Italy), reinforced with *Cynodon dactylon* (Bermuda grass) roots, were tested under drained triaxial compression and extension stress paths. The full experimental campaign includes unsaturated tests, which are currently in progress, and fully saturated tests, the preliminary results of which are presented in this paper. Results show that roots improve soil shear strength and affect its stress-strain response, with effects depending on the loading path and RVR. These findings provide new insight into the hydro-mechanical reinforcement of rooted pyroclastic soils and support nature-based strategies for shallow landslide mitigation.

Keywords: rooted soils; pyroclastic soils; Bermuda grass

1 INTRODUCTION

Rainfall-induced shallow landslides is a natural hazard in the Campania region of Southern Italy, where steep slopes are covered by loose and unsaturated pyroclastic deposits. During intense rainfall events, infiltration leads to a rapid decrease in matric suction, resulting in a loss of shear strength, triggering flow-like landslides. Historical disasters such as Sarno (1998, 160 fatalities), Nocera Inferiore (1997, 2005), and recurrent events in Ischia (2006, 2022) clearly demonstrate the severe socio-economic consequences of these phenomena, highlighting the urgent need for effective stabilization strategies. So far, the triggering mechanisms of flow-like landslides are still not fully understood, particularly regarding the transition from suction loss to the rapid occurrence of failure. The prediction of rainfall-induced events remains challenging due to the strong coupling between hydraulic processes, soil structure, vegetation and meteorological conditions (Damiano, 2019; Fraccica *et al.*, 2019). The PROMISE project ("Integrated appROach for MItigation of flowSlidE risk: full-scale test and advanced numerical modelling") (Pirone *et al.*, 2025) is currently addressing these issues through full-scale rainfall experiments and numerical modelling of monitored slopes in Campania. In this context, nature-based solutions employing vegetation have shown great potential for enhancing slope stability by combining hydrological and mechanical reinforcement effects (Foresta and Cascini, 2020; Leung *et al.*, 2021). The presence of vegetation contributes to slope stability through hydrological and mechanical effects. Hydrologically, vegetation influences rainfall infiltration and suction dynamics through canopy interception, transpiration, and root water uptake (Sidle *et al.*, 2017). Mechanically, the presence of roots provides additional resistance by increasing apparent cohesion and tensile strength, effectively reinforcing the soil matrix (Foresta and Cascini, 2020). Recent studies have demonstrated that root systems not only provide mechanical reinforcement but also modify the hydraulic properties of unsaturated soils, influencing water retention and conductivity (Leung *et al.*, 2015, Leung *et al.*, 2023). Boldrin et al. (2021) quantified these combined effects in full-scale vegetated slopes, showing that both hydrological and mechanical reinforcements depend strongly on plant type and maturity. Despite these advances, data on the hydro-mechanical reinforcement of pyroclastic soils remain scarce. In particular, the influence of root density, expressed as the root volume ratio (RVR), under different stress paths. To fill this gap, this work investigates the hydro-mechanical behaviour of a pyroclastic soil reinforced with *Cynodon dactylon* (Bermuda grass) roots under stress paths representative of shallow slip surfaces. Preliminary results from saturated drained triaxial tests highlight the dependence of soil strength and volumetric behaviour on RVR, providing insight into root reinforcement mechanisms relevant to nature-based slope stabilisation.

2 MATERIALS AND METHODS

2.1 *Materials*

A natural pyroclastic soil originating from the volcanic event of Vesuvius in 79 A.D. was retrieved at the Salerno site (coordinates: 40°41′51″N, 14°45′16″E) for testing in this study. The soil has the same geological context as the test site investigated within the PROMISE project (Pirone *et al*., 2025), providing a representative material for analysing the hydro-mechanical processes that govern slope instability. The in-situ stratigraphy of the Salerno site is comparable to the well-documented profile of Monte Faito (Guglielmi et al, 2023; Dias et al, 2022). In particular, the soil tested in this study was sampled from the shallower layers, classified as A1-A2 by Dias *et al.* (2022) and Vitiello *et al.* (2025). It represents the typical pyroclastic shallow cover (0.8 – 2 m depth) found in Campania region (Southern Italy), which is frequently involved in flow-type landslides (Pirone *et al.*, 2015, Olivares *et al.* 2003). The soil is a silty sand with a specific gravity of 2.65 (Vitiello *et al,* 2025), and it is characterised in-situ by a very loose structure with a natural soil porosity ranging between 0.50 and 0.65.

2.2 *Sample preparation*

A standardised sample preparation protocol was established to ensure methodological rigour and the comparability of bare and root-reinforced specimens. Cylindrical samples with dimensions of 76 mm in diameter and 152 mm in height were reconstituted using static compaction technique, in order to provide precise control over the dry density of the sample. A target porosity of n = 0.45 (void ratio e = 0.82) was maintained for all samples. Although lower than in-situ values, this porosity was selected to ensure the mechanical stability of the bare specimens throughout the laboratory testing procedures. Rooted specimens were prepared in the same way as the bare ones up to the compaction stage. Following this, the surface of the specimens was seeded with *C. dactylon* at a density of 34 g/m². The seeded samples were then subjected to a two-phase growth process to establish a mature root system: initially, they were placed in an outdoor environment for three months under natural ambient conditions to allow for germination and initial root development. Subsequently, in order to boost growth, the samples were transferred to a controlled growth chamber for a period of four months. The chamber was maintained at a constant temperature of 29 °C ± 1 °C and 60% ± 1% relative humidity, with 12 hours of light per day.

2.3 *Roots tensile strength*

The tensile strength of the *C. dactylon* roots was characterized through uniaxial tension tests. A total of 51 tensile tests were performed on individual roots. Even if natural morphological variation was present, roots were selected for uniformity and the diameter was taken as average along the length. Diameter values, measured before testing, ranging from 0.10 mm to 0.69 mm. The tests were conducted using a universal material testing machine (Model EZ50, Lloyd Instruments). A 50 N capacity load cell with an accuracy of ± 0.1% was used to measure the tensile force applied at a constant displacement rate of 5 mm/min until failure. The roots were clamped between two rubber-lined grips to prevent them from slipping during extension. No assessment of diameter change was conducted after the tests. Figure 1: a) tensile strength b) tensile force of Cynodon Dactylon roots as function of root diameter Figure 1a) and Figure 1b) show the relationship between root diameter and, respectively, the tensile strength and force. It is observed that the tensile strength, σ_{max}, decreases as the root diameter increases, while the tensile resistance, F_{max}, increases as the root diameter increases.

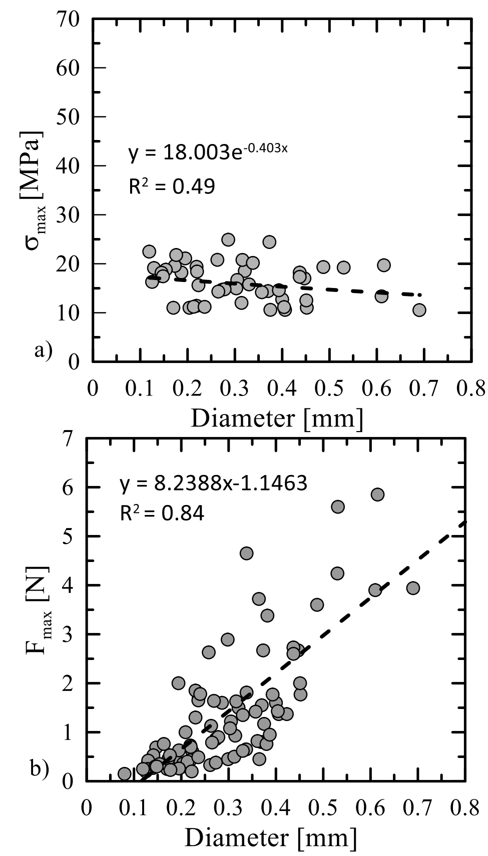

Figure 1: a) tensile strength b) tensile force of Cynodon Dactylon roots as function of root diameter

2.4 *Experimental setup and test procedures*

To characterize the mechanical behaviour of the soil under different conditions, triaxial tests were conducted using a standard CKC triaxial apparatus at the Geotechnical laboratory of the Hong Kong University of Science and Technology. Isotropic consolidated drained triaxial tests were conducted on saturated samples. Both compression and extension stress-paths were investigated for each condition to represent critical in-situ conditions along potential slip surfaces. Given the limited depth of the deposit from which the soil originates, an effective confining pressure (σ'_3) of 50 kPa was selected for all tests to represent in-situ stress conditions. The strain rate applied in both the extension and compression tests was 0.04%/min. The RVR for the rooted specimens was determined at the end of each test. For each tested specimen, the root system was extracted by washing away the soil. The cleaned roots were then scanned at a high-resolution scanner (EPSON scanner, model: STD4800) and the resulting images were analysed using Pro–WinRHIZO software system to obtain precise measurements of root diameters, lengths and volume. The RVR was calculated as the ratio of roots volume to the total volume of the soil sample (RVR = V_{roots}/V_{tot}). Table 1 summarises the tests reported in this study.

Table 1: Testing programme summary

ID test	Sample type	Stress path	Suction (kPa)	RVR (%)
CB50S	Bare	Compression	0	0
EB50S	Bare	Extension	0	0
CV150S	Rooted	Compression	0	0.50
EV150S	Rooted	Extension	0	0.50
CV250S	Rooted	Compression	0	0.10
EV250S	Rooted	Extension	0	0.10

3 RESULTS AND DISCUSSION

Figure 2 depicts the results of consolidated drained triaxial tests on bare and rooted pyroclastic specimens under fully saturated conditions, for different values of RVR. During the growth period, the rooted specimens were subjected to wetting–drying cycles as a result of irrigation. Consequently, the void ratio, and hence porosity, was altered by the combined effects of these cycles and root growth. The changes of porosity are summarised in Table 2.

Figure 2a) shows the root effects on resistance on the deviatoric stress (q) – axial strain (ε_a) plane. Under the compression path ($\varepsilon_a > 0$), both the bare and rooted specimens exhibit similar ductile–contractive behaviour and comparable peak deviatoric stresses (~160 kPa for a confining pressure of σ_c = 50 kPa). This phenomenon suggests that the presence of roots has a limited impact on the soil resistance under compression paths. This result is consistent with the findings by Karimzadeh *et al.* (2021). The root orientation was predominantly parallel to the direction of the major principal stress during triaxial compression. This means that, during the shearing phase, the roots do not completely mobilise their tensile strength to reinforce the soil.

Table 2: Porosity changes

ID test	n initial	RVR (%)	n post roots growth
CB50S	0.45	-	0.45
EB50S	0.45	-	0.45
CV150S	0.45	0.50	0.43
EV150S	0.45	0.50	0.43
CV250S	0.45	0.10	0.46
EV250S	0.45	0.10	0.47

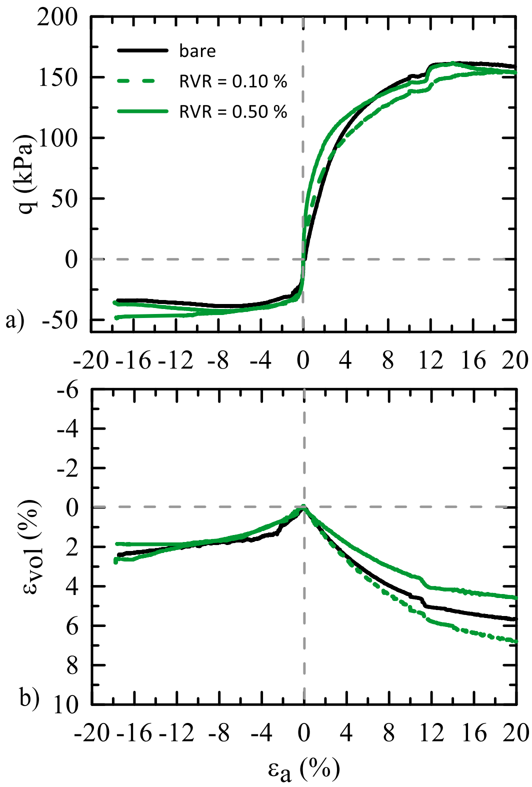

Figure 2: a) stress – strain and b) volumetric responses of fully saturated triaxial tests as the RVR changes

However, the rooted specimens with a higher RVR (= 0.50%) displayed slightly higher rigidity than the others. As shown in Figure 2b), all the samples show a contractive behaviour. The sample with RVR = 0.50% shows a smaller volumetric deformation, suggesting that the presence of roots counteracts the soil contraction during shearing. Conversely, under extension paths ($\varepsilon_a < 0$), the presence of roots became more prominent. The rooted specimen with RVR = 0.50% (green continuous line, Figure 2a) exhibit a much higher values of q (~49 kPa) than the bare one (~35 kPa), with about 40% increase in terms of resistance. On the contrary, the rooted specimen with RVR = 0.10% (dashed green line, Figure 2) shows a stiffer initial response (up to approximately $\varepsilon_a \sim 3\%$)

compared to the bare soil, and reaching a q (~37 kPa), bigger than the bare case but smaller than the specimen with greater RVR, although the difference is almost negligible (only 5% increase in resistance). This trend suggests a direct relationship between the quantity of roots present in the sample and the improvement in the mechanical characteristics of the soil, highlighting the importance of achieving sufficient RVR to obtain significant mechanical benefits. Both the bare and root specimens exhibited a contractive volumetric behaviour during shearing. As under the compression path, the rooted specimen with RVR = 0.50% displays a less contractive behaviour, though this effect in this case is less pronounced than that observed along the compression path. It should also be noted that the presence of roots did not affect the failure mode of the samples, which all exhibited barrel-shaped deformation.

4 CONCLUSIONS

An ongoing experimental study aims to characterize the mechanical behaviour of a pyroclastic soil reinforced with *C. dactylon* roots, considering both fully saturated and unsaturated conditions. This paper presents the preliminary results of drained triaxial tests under fully saturated conditions. The results show that the influence of root reinforcement on the mechanical behaviour of pyroclastic soil is dependent on the stress path and RVR. Under compression, the effect of roots is almost negligible, except for a variation in the volumetric behaviour of the material. Conversely, the presence of roots enhances the mechanical behaviour of the soil under extension path, where the tensile strength of the roots is largely mobilised. In this case, the high RVR led to a substantial increase in shear resistance, highlighting a direct correlation between the RVR and soil improvement. This finding confirms that achieving a sufficient RVR is essential to have a significant mechanical benefit, particularly in stabilising slopes where extensional paths play a key role.

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