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Long rooted grass in natural pyroclastic soil

M. Moscariello[1], R. Ciaglia[1], V. Foresta[1], S. Cuomo[1]

[1]*University of Salerno, Department of Civil Engineering, Via Giovanni Paolo II, 132, 84084 Fisciano, (SA), Italy*

ABSTRACT: Natural-inspired solutions for mitigating natural hazards are increasingly requested by society because they offer multiple co-benefits for human health, the economy and the environment. It is well established that vegetation increases soil strength, while root water uptake and canopy cover contribute to reducing pore water pressure. This study examines the mechanical interaction between roots and soil for two fine, long-rooted grass species grown in Vesuvian pyroclastic soil from southern Italy. Direct shear tests on unsaturated, undisturbed specimens collected at 5, 17, and 38 months after seeding were used to assess how vegetation development influences soil shear strength. The interpretation of the experimental results considers an additional phase associated with root occupancy in soil pore space, which affects soil porosity. A perpendicular root-reinforcement model is adopted, assuming that the root area ratio is equivalent to the root volume ratio. These assumptions supported the estimation of distinct shear strength envelopes for different root volume ratios.

Keywords: root-soil interaction; mechanical behavior of vegetated soil; long-rooted grass; pyroclastic soils

1 INTRODUCTION

The use of vegetation as an eco-sustainable approach to landslide risk mitigation has gained increasing attention in recent years. Root systems enhance the hydro-mechanical properties of soil, improving slope stability and reducing susceptibility to specific failure mechanisms (Cuomo et al., 2024). Vegetated soils can be regarded as composite materials, in which the soil matrix is reinforced by a network of roots.

Two main approaches have been proposed to model root–soil interaction: (i) estimation of maximum reinforcement as the sum of individual root contributions (Wu, 1976; Pollen and Simon, 2005; Schwarz et al., 2010, 2013) and (ii) modeling the mutual influence between roots and the surrounding soil (Mao et al., 2014; Liang et al., 2015). In this study, the first approach is adopted, expressing the shear strength of vegetated soil as the sum of four components (Veylon et al., 2015), due to: effective cohesion, friction resistance, matric suction, and root reinforcement.

Typically, the root contribution is represented as an apparent increase in soil cohesion, while variations in friction angle are less common and often depend on root orientation during shearing (Gray and Ohashi, 1983). Contrasting evidence has also been reported; for example, Rickli and Graf (2009) observed an increase in friction angle of about 5° without any additional cohesion in triaxial tests, suggesting that root reinforcement increase may be stress dependent. Maffra et al. (2019) found that roots increase shear strength in both sandy and clayey soils, enhancing both cohesion and friction angle. The increase in friction angle observed in fine soils was attributed to the density and spatial distribution of roots along the failure surface. Overall, these findings highlight the key role of root architecture in controlling both soil reinforcement and plant stability.

The present study investigates the interaction between two long-rooted grass species and Vesuvian pyroclastic soils under both saturated and unsaturated conditions through direct shear testing.

2 MATERIAL AND METHODS

The soil–root interaction was analyzed with reference to a volcanic soil and two grass species characterized by deep and extensive root systems. At this aim direct shear tests in saturated and unsaturated condition were carried out on undisturbed soil samples collected from a monitored experimental site in Nocera Inferiore (Southern Italy). The species were planted in June 2021 and subsequently monitored through periodic measurements of soil suction, water content and through the data of cumulated daily rainfall and the daily minimum and maximum atmospheric temperature data acquired from a weather station of Campania Region located close to the experimental field setup (Cuomo et al., 2024). Complementary geotechnical surveys were also performed at regular intervals to document root growth. Specimens were collected at 5 (November 2021), 17 (October 2022), and 38 months (August 2024) after planting to capture the early establishment, intermediate growth, and mature stages of vegetation, allowing assessment of the temporal evolution of root reinforcement and its influence on soil shear strength.

Direct shear tests were performed on undisturbed soil specimens, both in their natural state and after root

growth, to assess the influence of vegetation on shear strength parameters. All the tests were carried out in a standard equipment on specimens with side 60 mm and height 35 mm at (i) natural water content, which is representative of field condition, and (ii) under fully saturated conditions, to simulate extreme wetting scenarios. A wide range of normal stresses, from 35 kPa to 150 kPa, was applied to capture soil behavior from near-surface shallow stress conditions to deeper stress states.

The two species selected, later named as VEG2 and VEG3, are fine, long-rooted perennial graminae belonging to the C3–C4 intermediate group. These grasses can switch between C3 and C4 photosynthetic pathways depending on environmental conditions. The C3 pathway is more efficient in cool, moist climates, whereas the C4 pathway enhances carbon fixation and water-use efficiency under hot, dry, and sunny conditions, allowing the plants to maintain high productivity across variable environments (Ehleringer and Cerling, 2002; Szarek, 1975).

Their ability to shift from C3 to C4 metabolism allows continuous root growth under varying climatic conditions. This allows for the development of a root system capable of enhancing soil shear strength across diverse environmental conditions. Moreover, the two grass species exhibit distinct root morphologies (Fig. 1). The root system of VEG2 is composed of thin roots coated with a jelly-like substance that enhances adhesion to soil particles and modifies the retention properties of vegetated soil (Fig. 1a). In contrast, VEG3 develops a tap system with one large central fibrous root and multiple short and finer lateral branches.

The species also differ in their overall root architecture. VEG2 forms a dense, well-distributed network of vertical and horizontal roots of a similar diameter while VEG3 is dominated by large vertical roots with a few smaller horizontal branches (Fig. 1b).

In addition, the above-ground growth was monitored through periodic measurements of foliage height. Field observations showed that foliage height stabilized after the first year of growth and exhibited no significant variation in subsequent years. This trend persisted even during short dormancy phases, during which the plants underwent drying but later recovered their vegetative functions. The rooting depth of both VEG2 and VEG3 reached approximately 1 m within the first year after seeding and remained nearly constant throughout the subsequent life cycle of the plants. Root development in terms of diameter and volume was measured from roots within the specimens used for direct shear testing.

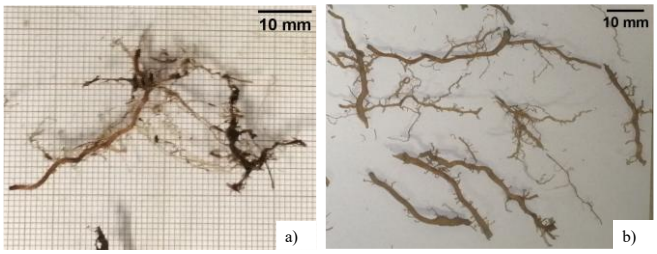


Figure 1. Roots of a) VEG2 and b) VEG3

The in-situ soil is a sandy silt derived from eruptive activities of Monte Somma-Vesuvio, which forms widespread cover deposits across Southern Italy.
These soils usually exhibit a high porosity, and high variability in suction and hydraulic conductivity, all of which strongly affect their hydro-mechanical behavior (Moscariello et al., 2021). In this study, the bare soil shows a specific gravity Gs = 2.7, and average porosity 0.57 (range 0.50–0.67; Moscariello et al., 2021).
Triaxial and direct shear tests on undisturbed saturated specimens show low cohesion (<15 kPa) and friction angles between 36° and 41° (Sorbino and Nicotera, 2013).

In Cuomo et al. (2024), soil water retention curves (SWRCs) were determined using a multi-instrument approach for vegetated and bare soil in the test site. The curves were derived from periodic measurements of matric suction and volumetric water content in the field, obtained through tensiometers and low-cost soil moisture sensors at the depth of 20 cm. The air-entry value (AEV) of the bare soil was determined to be 13.3 kPa. The inclusion of roots significantly increased this threshold, with VEG2 exhibiting an average AEV of 27.3 kPa and VEG3 reaching 36.4 kPa (Cuomo et al., 2024). In contrast, the presence and subsequent growth of roots did not alter the trends of the saturated or residual volumetric water contents (θ_{sat} =0.51 - 0.72, θ_{res} =0.00 - 0.12). These results indicate that root reinforcement primarily influences the air-entry value and desaturation behavior, with minimal effect on the soil's water-holding capacity at full saturation or residual conditions. Moreover, these measurements are essential for interpreting laboratory shear tests and assessing the temporal hydro-mechanical impact on vegetated soil.

2.1 Framework for the interpretation of the results

In a rooted soil, the root volume ratio (mm^3/mm^3), indicated as $R_v = V_r/V_s$, is defined as the total volume of roots (V_r) per unit volume of soil (V_s).

The experimental results were interpretated assuming that unsaturated vegetated soil contains air, water, solid phases and a further phase associated with root occupancy in soil space (Ng et al., 2016). Thus, a term for the pore volume occupied by roots is required. In this paper, the void ratio is estimated though the equation proposed by Ng et al. (2016):

$$e = \frac{e_0 - R_v(1+e_0)}{1+R_v(1+e_0)} \quad (1)$$

where e_0 is the void ratio of bare soil (i.e., before root permeation).

The effective stress of unsaturated soil specimen was estimated through the relation proposed by Bishop (1959), and the failure criterion was estimated as follow:

$$\tau_f = c' + [(\sigma_v - u_a) + S_r \cdot s] \tan \varphi' \quad (2)$$

where c′ is the effective cohesion, $(\sigma_v - u_a)$ is the net vertical stress, φ' is the effective friction angle, s is the matric suction and $S_r = \theta/n = \theta \cdot (1+e)/e$ is the saturation degree.

3 RESULTS

The direct shear tests encompass three growth stages—5 and 17 months (Cuomo et al., 2024) and 38 months—enabling assessment of the progressive evolution of shear strength throughout the full development cycle of the vegetation.

The shear strength envelopes of VEG2 and VEG3 reported by Cuomo et al. (2024) are characterized by the following strength parameters: for VEG2, c'=42 kPa and φ'=27°; and for VEG3, c'=29 kPa and φ'=37°.

In this paper, the shear strength data were interpreted using two approaches: (i) by considering the complete set of tests for each species, and (ii) by grouping the tests according to their root volume ratio. The second approach, which considers the variation of R_v with depth, can also be interpreted as grouping the data by sampling depth. Specifically, the highest R_v values are observed in the uppermost layer (0–0.10 m), while lower values are recorded at greater depths (0.10–0.30 m) for both grass species.

The failure criterion derived from the complete dataset of each species indicates that VEG2 exhibits a cohesion of 19.35 kPa and a friction angle of 35.80° (Fig. 2a), whereas VEG3 shows a cohesion of 19.20 kPa and a friction angle of 38.54° (Fig. 3a). The strength envelopes obtained for both fully and partially saturated rooted specimens are mutually consistent and lie above that of the bare soil. However, these values differ significantly from those reported by Cuomo et al. (2024), suggesting that plant growth and changes in roots diameter and in spatial dispositions may induce measurable variations in the soil's shear strength parameters. The comparison between vegetated and non- vegetated soils indicates that roots not only enhance shear strength but also increases variability in the experimental data, as shown by the lower R2 values for vegetated specimens. Classifying results by root volume ratio yields more consistent and reliable shear strength interpretations. For VEG2, specimens with low R_v ($0.001 \leq R_v \leq 0.009$) show reduced friction angle and increased cohesion, similarly high R_v (≥ 0.01) leads to a further increase in cohesion and a slight decrease of friction angle (Fig. 2).

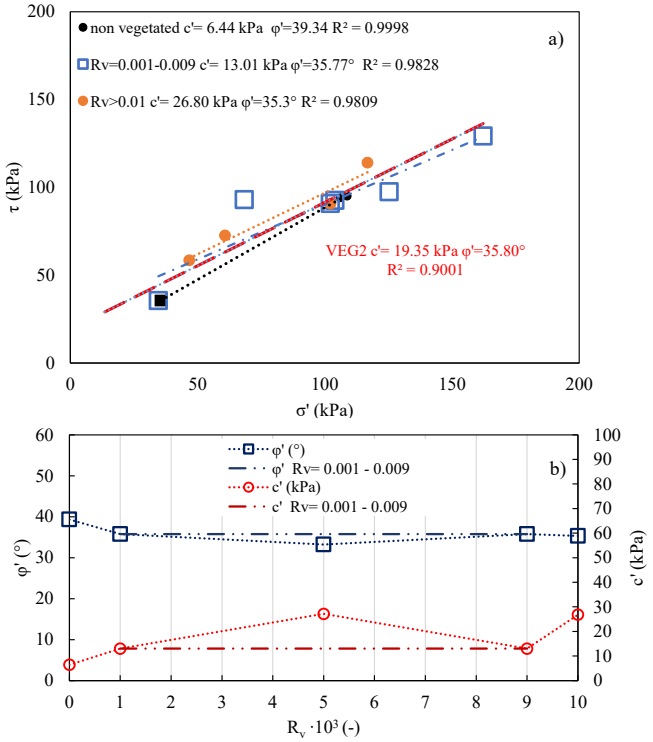


Figure 2. a) Shear strength envelope for VEG2 species with different root volume ratio (R_v); b) trend of cohesion and friction angle obtained by failure envelope as a function of R_v

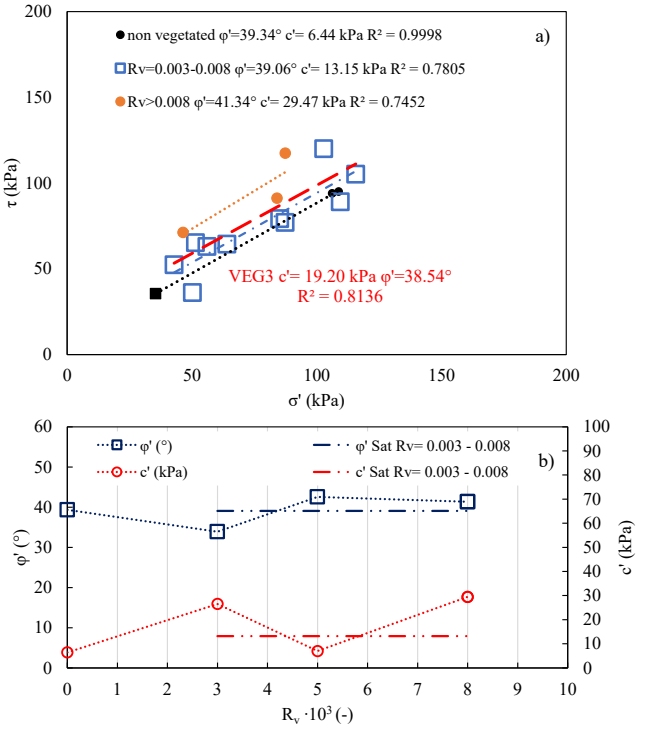


Figure 3. a) Shear strength envelope for VEG3 species with different root volume ratio (R_v); b) trend of cohesion and friction angle obtained by failure envelope as a function of R_v

For VEG3, two representative R_v intervals ($0.003 \leq R_v \leq 0.008$ and $R_v \geq 0.008$) were identified: lower R_v values correspond to an increase of cohesion, while higher

R_v values result in higher friction angle and cohesion, albeit with greater uncertainty (Fig. 3).

When results are restricted to narrower R_v classes (i.e. R_v = 0.003 and R_v =0.005), the uncertainty is reduced and R2 values increase, confirming that R_v can capture the influence of roots on vegetated soil behavior (Fig. 3b).

Moreover, considering the contrasting root architectures, the differences in shear strength can be attributed to different growth mechanisms: in VEG2, reinforcement primarily results from the progressive development of a dense root network with uniform diameter and different orientation, whereas in VEG3, it is mainly driven by the thickening of primary roots and the increasing number of lateral branches.

Changes in porosity are also evaluated (Eq. 2) to estimate the effect of root growth. Non-vegetated specimens showed an average initial porosity of 0.57 in agreement with literature values, whereas vegetated specimens exhibited a consistent reduction. For VEG2, the average porosity was 0.51 at 5 and 17 months (range 0.47–0.56) and further decreased to 0.50 at 38 months (range 0.47–0.53). For VEG3, the average porosity was 0.49 at 5 and 17 months (range 0.46–0.53) and declined more markedly to 0.43 at 38 months (range 0.38–0.48).

4 CONCLUDING REMARKS

The study shows that roots improve the shear strength of unsaturated soils prone to shallow landslides, though they also introduce greater variability. Root reinforcement mainly enhances cohesion, while friction angle changes are associated with root orientation.

Root volume ratio (R_v) proves to be a physically meaningful parameter for characterizing root reinforcement, as it directly represents the actual root content in each specimen. R_v-based classification reveals distinct strength behaviors: specimens with low R_v exhibit high cohesion and reduced friction angle, while high Rv specimens show increases in both parameters.

Further studies should quantify the influence of root orientation, architecture, and hydro-mechanical coupling through tests with controlled root inclinations, varying R_v in a wider range of values, and different stress conditions. Moreover, further in situ tests should be performed to go beyond the limitation of the experimental approach shown in the paper (i.e. representativeness of the specimens).

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