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EXPLORING STRESS-PATHS AND VEGETATION REINFORCEMENT MECHANISMS IN A COMPACTED SOIL

Alessandro FRACCICA[1], **Enrique ROMERO**[2]

ABSTRACT

The use of vegetation is a sustainable technique to mitigate the risk of landslides and erosion phenomena. The reinforcement of roots on soils is complex and depends on their morphological and mechanical characteristics and the stresses that develop at the soil-root interface. Many models have been produced in literature to infer the increase in soil shear/tensile strength due to roots. However, many of these models give limited consideration to the effects of soil hydraulic conditions and soil volume changes.

Large cell triaxial compression tests, oedometer test, uniaxial tensile tests and volume change tests upon drying were carried out to explore the mechanical effects of vegetation on a compacted soil at low confining stresses and at different hydraulic states. Root features were assessed through X-ray tomography for each soil specimen in order to compare the different laboratory tests carried out.

Different stress-strain responses were observed during the mechanical tests, depending on the hydraulic state of the specimens. Two soil reinforcement mechanisms were observed (roots breakage and slippage), particularly in uniaxial tensile tests. Such mechanisms in turn impacted the mechanical behaviour of the vegetated soil. Volume change behaviour and microstructural effects of roots on soil influenced the macrostructural mechanical response, too. Despite an increase in shear strength, vegetated specimens showed larger volumetric deformations upon shearing and a delayed reinforcement activation, close to saturation.

Results were jointly interpreted within the Barcelona Basic Model, allowing to trace the effects of roots and two hydraulic states on the yielding behaviour of the tested specimens following the different stress-paths presented.

Keywords: triaxial compressions, oedometer tests, uniaxial tensile tests, soil-root interactions, soil yielding, soil volume change.

INTRODUCTION

Vegetation root reinforcement has traditionally been evaluated by large direct shear tests, both in situ and in the laboratory (Yildiz et al, 2018), and by standard or large triaxial equipment (Karimzadeh et al., 2021; Fraccica, 2019). However, root effects on soil hydro-mechanical behaviour under non-conventional stress paths—particularly tensile and oedometer tests and upon suction changes—remain unexplored (Fraccica et al., 2022; 2024). Vegetation reinforcement highly depends on stresses that develop at the soil-root interface: pull-out tests performed by Pollen (2007) suggested that such stresses are affected by root failure mechanisms at different soil moistures: in poorly saturated soils, root breakage dominates, while in nearly saturated ones, slip-out is more common. Microstructural effects of roots in soil, including pore clogging, soil particle re-orientation, fissure creation, aggregate cracking, mucilage production (Carminati et al., 2010; Lu et al., 2020) have effects on soil volume change and its related hydro-mechanical behaviour. Therefore, reinforcement models which couple volume change behaviour and hydraulic states to soil stress states would be desirable. Hence, the objectives of this study are to (a) present novel laboratory results obtained by testing a vegetated clayey sand under different stress paths and hydraulic states, (b) explore the interpretation of these tests with an appropriate constitutive law for unsaturated soils.

SOIL PROPERTIES AND COMPACTION

The clayey sand used in this study has been characterised by Fraccica (2019). It was statically compacted dry of optimum, then seeded with Cynodon Dactylon. Compacted specimens were finally watered, under unconfined conditions, to a matric suction around 1 kPa, kept constant throughout the entire process of plant growth. After vegetation establishment, specimens were

1 *Dr. Eng., Italian Institute for Environmental Protection and Research, Rome, Italy, alessandro.fraccica@isprambiente.it*
2 *Prof. Eng., Geomechanics Group, International Centre for Numerical Methods in Engineering / Universitat Politècnica de Catalunya, Barcelona, Spain, enrique.romero-morales@upc.edu*

kept in a controlled-atmosphere room (T = 20°C, RH = 50%) until reaching the desired suction for testing. Bare soil samples were subjected to the same procedures for the sake of comparison (Fraccica et al., 2022; 2024). Soil physical properties, mechanical parameters, and as-compaction state are presented in Table 1. Triaxial specimens (200 mm dia., 400 mm high), oedometer specimens (150 mm dia., 70 mm high) and tensile specimens (2 moulds of 100 mm dia., 40 mm high held together by a 50 mm wide and 32 mm long bridge, see Fraccica et al. 2022) were prepared in vegetated and bare conditions. Root volumes were assessed through X-ray tomography for each soil specimen and normalised to the bulk soil volume (Root volume ratio, $R_v = V_{roots}/V_{soil}$ see Fraccica et al., 2024).

VOLUME CHANGE UPON DRYING

Volumetric changes upon suction were evaluated by paraffin tests on cubes of 40 mm side. For vegetated specimens, roots volumes, soil dry mass and gravimetric water content were assessed to compute the void ratio (Fraccica et al., 2024) according to its classical formulation. Hence the volumetric strain upon suction ($\varepsilon_{vol,s}$) was evaluated according to equation 1:

$$\varepsilon_{vol} = \frac{\Delta e}{1 + e_0} \qquad (1)$$

Results are provided in Figure 1: vegetated specimens showed higher void ratios than the bare ones, hence remained at lower volumetric strains.

Table 1 Soil properties, parameters, compaction state

Soil properties/ parameters / compaction state	Value
USCS classification	SC
Compaction dry density (Mg/m3)	1.60**
Compaction gravimetric water content (%)	15**
Suction at compaction (kPa)	40**
Compaction max vertical stress (kPa)	100**
q - p' failure envelope slope, Mc (bare/vegetated)	1.42 / 1.45[a]
apparent cohesion (bare/ vegetated), c' (kPa)	0/10.3[a]
pre-yield stiffness for suction changes, κ_s (bare/veg.)	0.002/ 0.001**
post-yield stiffness for suction changes, λ_s (bare/veg.)	0.011/0.009**

** Fraccica et al. (2024) a Fraccica et al. (2023)

They were interpreted within the context of Barcelona Basic Model (BBM, Alonso et al., 1990) along pre- and post-yield states: their respective stiffness parameters are provided in Table 1. Such behaviour is due to the microstructural changes induced by roots in the matrix (macro-pores generation and concomitant soil-root shrinkage upon suction), as observed in X-ray where roots were found to be often surrounded by void channels and as formalised quantitatively in Fraccica et al. (2024).

OEDOMETER COMPRESSION

Figure 2 presents oedometer tests under saturated conditions (suction, s = 0 kPa) and at constant water content. Results on partially saturated specimens were interpreted in terms of net mean stress p'', as proposed by Alonso et al. (1990), adopting a K_0 derived from Jaky's formulation, assuming negligible variations within

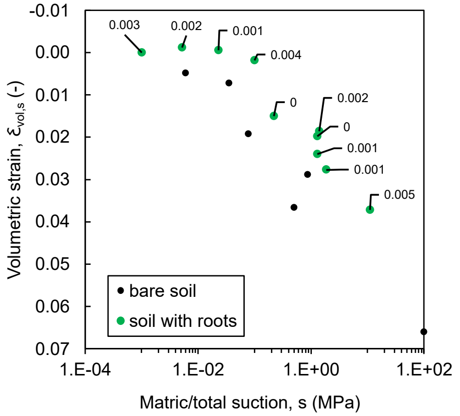

Figure 1 *Volumetric strain evolution upon suction. R_v values provided as labels*

the suction range investigated (Romero, 1999).

Some contrasting trends were observed: in saturated soil, vegetation reduced yield stress and pre-yield stiffness, while reaching a higher stiffness at high stresses only. At larger matric suction, vegetation provided higher stiffness and yield than bare soil. It can be inferred that, when soil is saturated, microstructural changes (macro-pores/fissures) induced by roots are prevailing over reinforcement in the pre-yield states, while a "stolen void" mechanism is ruling the slight increase of stiffness at high stresses (at which macro-pores/fissures have collapsed). Apart from macro-pores, suction is also inducing roots mucilage production, which is solidifying around root tips generating aggregates that allow a firm contact between root tips and soil (Carminati et al., 2010). Such chemo-physical vegetation behaviour could be ruling this soil mechanical behaviour. Some slight effects of roots were observed along the unloading-reloading stress-strain states, where root decompression appears to allow a higher recovery of elastic deformation.

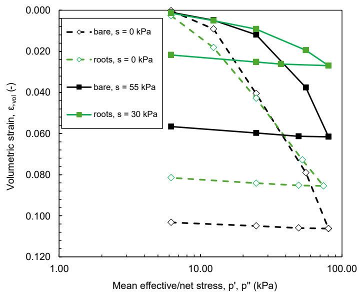

Figure 2 *Oedometer tests on bare and rooted samples (initial matric suction indicated in the legend). R_v = 0.015 in vegetated samples*

UNIAXIAL EXTENSION

Figure 3 presents results of uniaxial tensile tests at different suction. Roots improved soil tensile strength at both lower and higher suction values. However, close to saturation (i.e. s = 4 kPa), roots required higher displacements than bare soil to provide a strength enhancement and they were observed to be totally pulled out the tensile crack, without breaking. On the contrary, higher suction (i.e. above s = 30 kPa) led to roots breakage in correspondence with the tensile crack, coupled with a more abrupt strength loss in the post-peak. Before peak, a quicker activation of the reinforcement is observed in the vegetated soil (Figure 3). Results were interpreted within the mean net stress (p") - deviatoric stress (q) space, considering $\sigma_3 = \sigma_t$ and the other total stresses to be null, according to Fraccica et al. (2022). Particle Image Velocimetry (PIV, Fraccica et al., 2022) allowed to follow the axial strain fields on the specimens' surface during the tests and to observe that, around the tensile stress peak, the soil area in which strain develops was larger in the specimens with vegetation. Yield stresses were evaluated on the p" - d (d: horizontal displacement) curves resulting from the tensile tests, given that similar values of axial strain were observed by PIV at similar horizontal displacements (Fraccica et al., 2022).

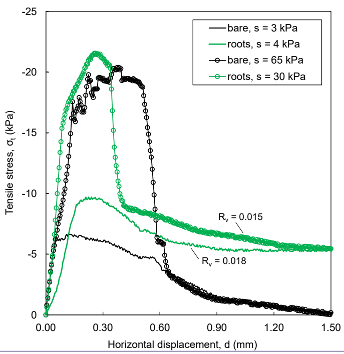

Figure 3 *Uniaxial tensile tests (average test matric suction indicated in the legend). R_v indicated as labels*

TRIAXIAL COMPRESSION

Figure 4 (upper,lower) provides results from constant water content triaxial compressions (Fraccica, 2019). At similar confining stresses and suction, roots improved the shear strength. The interpretation of all the tests, considering end-of-test stresses (Fraccica, 2019; 2023) within a failure criterion for partially saturated soils showed that vegetation contributed to increase soil cohesion, with minor effects on the friction angle, too (Table 1). Yield stresses for triaxial compressions were evaluated within the p" - ε_{vol} space (Figure 4-lower), similarly to what has been done for the oedometer tests. As observed, roots provided higher yield stress and shear strength within a soil at a matric suction of 25 kPa, with respect to a bare soil at a matric suction of 70 kPa

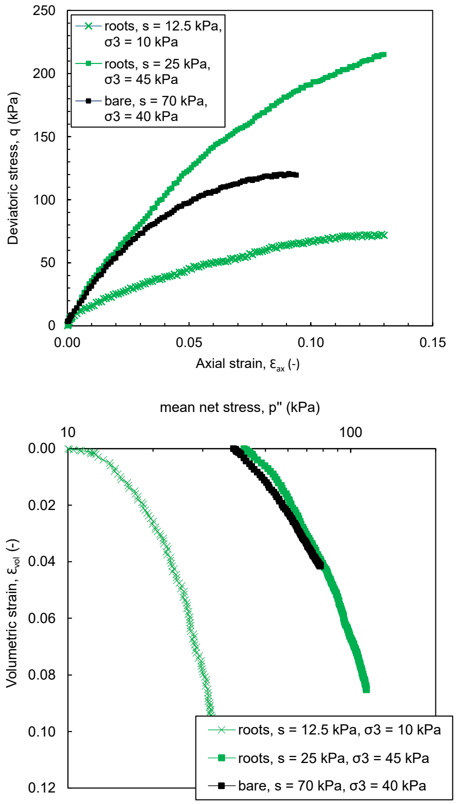

Figure 4 *Triaxial compressions at constant water content. Initial suction values and confining stresses in the legend. Rv = 0.016 in vegetated samples. A) q-ε_{ax} space, b) p"-ε_{vol} space*

RESULTS INTERPRETATION

Yield stress points obtained from the tests previously presented are placed in the p"-q space and interpreted within the BBM yield ellipse formulation proposed by Alonso et al. (1990) (see

Figure 5) and considering the slope values Mc calculated for bare and vegetated soils (see Table 1). Information about the isotropic preconsolidation stress (p0*) and the intersection value (p_s) with negative p'' is provided in Figure 5. The yield loci confirm a reduction of soil yield induced by roots at very low suction values, due to microstructural effects on soil and low shear stresses developing at the soil root interface (pull-out without breaking). At higher suction, the development of aggregates due to mucilage production makes stronger soil-root tips contacts, resulting in a better exploitation of the stiffness and tensile strength of the roots (for the tested species, 5 MPa, on average). This is, in turn, reflected in a consistent expansion of the yield locus corresponding to suction s = 30 kPa.

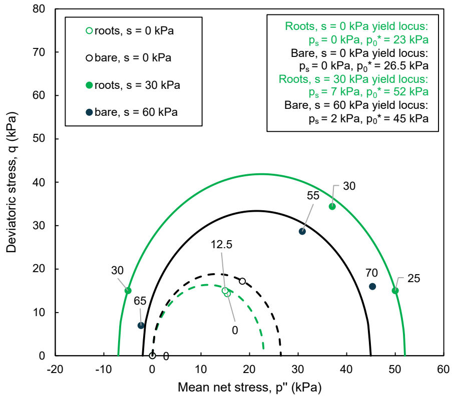

Figure 5 *Yield stress states and loci. Matric suction indicated as labels*

CONCLUSIONS

This study aimed at exploring the effects of different stress paths and different hydraulic states on the reinforcement of roots on soil. Soil hydro-mechanical behaviour is strongly associated with its volume change and the microstructural features generated by the roots. Roots generally improved soil shear strength. However, at low suction, root reinforcement is counterbalanced by their effects on soil micro-structure and is activated at large strains, by a fibre's pull-out mechanism. Larger suction values allow to exploit roots full reinforcement potential (by fibre's breakage) at smaller strains.

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