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Procedia Engineering 158 (2016) 45 – 50

Procedia Engineering

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VI ITALIAN CONFERENCE OF RESEARCHERS IN GEOTECHNICAL ENGINEERING –
Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale,
CNRIG2016

Experimental investigation on the mechanical contribution of roots to the shear strength of a sandy soil

Marco Mazzuoli[a],*, Rossella Bovolenta[a], Riccardo Berardi[a]

[a]*Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Via Montallegro 1, 16145 Genoa, Italy*

Abstract

A common soil-bio-engineering practice to prevent the erosion and the movement of soil along natural hill-slopes is the hydroseeding of herbs and shrubs, whose roots can contribute to the stability of the surficial layers of soil. So far a clear picture of the soil-roots interaction is still missing. In the present paper, the results of triaxial tests carried out both on soil-specimens naturally rooted by plants that are typical of the Mediterranean scrub (i.e. *spartium-junceum*, *ligustrum* and *arbutus-unedo*) and on samples reconstituted using the same material as the rooted ones, are reported. A discussion arises from the comparison between the results obtained on rooted and on reconstituted specimens. Moreover, high-precision measurements of the tensile stress of individual root fibers were also made. Finally, an interpretation of the mechanical contribution of roots to the soil strength under conditions mimicking the effect of an intense storm on the hill slopes is also provided.

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016

Keywords: reinforced soil; roots; triaxial tests; soil bio-engineering

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1. Introduction

The relevance of the contribution of roots to prevent the instability and the erosion of soil from hill slopes has been long observed and is in general recognised. Indeed, hydroseeding and shrub installations are often associated with bio- and traditional geotechnical-engineering works not only to preserve the landscape appearance, but because providing

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* Corresponding author. Tel.: +39-010-353-2379; fax: +39-010-353-2546.
E-mail address: marco.mazzuoli@unige.it

Peer-review under the responsibility of the organizing and scientific committees of CNRIG2016
doi:10.1016/j.proeng.2016.08.403

the deeply remixed soil with a natural coating supports the durability of the main geotechnical frameworks and complete their functionality. Certain species of herbs and shrubs can develop their root system in a few months, thereby rapidly supplying to the soil additional resistance to the run off erosion (e.g. [1,2] or [3] for a review of previous contributions) and to the nutrient removal as well as possibly stabilizing the surficial layers of soil in the meanwhile that trees develop deep roots and the natural equilibrium is restored [4–7].

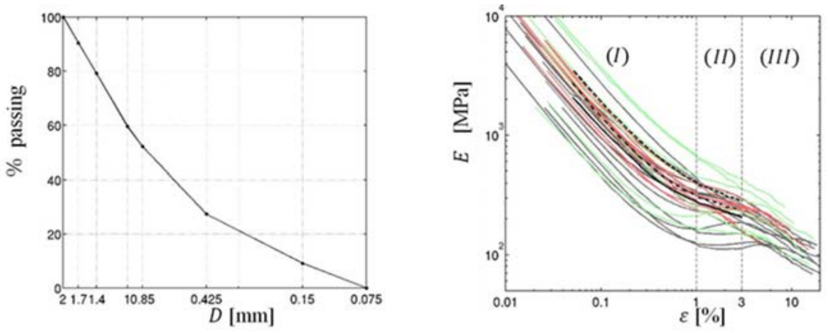

Fig. 1. Panel (a) shows the grain distribution of the material used of the TX tests. Panel (b) shows the Young modulus as a function of the axial strain of roots during the tension tests: green thin lines (SJ), black this lines (LI), red thin lines (AU). Values averaged by species are indicated with [- - -] (SJ), [—] (LI) and [-·-] (AU).

Nonetheless, a little is known as yet on the mechanism of reinforcement of roots. Even in the simplified case where roots are treated mechanically as fiber inclusions neglecting both biological and hydrological effects, a physically based approach to the problem is extremely difficult and, for this reason, a number of empirical formulae are available into the literature, which are often based on hypothesis that can be satisfied only in specific field conditions. In fact, the "architecture" of root framework (e.g. size, shape, thickness, space-distribution) as well as the mechanical properties of root material (i.e. stiffness, yield stress, structure, ductility, fiber-soil anchorage and adhesion) are strongly dependent on the plant species and on the environment in which they develop.

The *pull-out* of plants, i.e. the instrumented uprooting of plants in their natural site or in the laboratory, is a technique often used to estimate the strength enabled by roots as well as the slip friction at soil-roots interface [e.g. 8,9]. Although in principle the basic idea of the pull-out is simple, obtaining reliable estimates of the root-soil friction angle is far from being trivial, firstly because it is difficult to counterbalance the pull-out force contextually preserving the integrity of plants and soil, secondly because a large number of measurements is required for the convergence of statistics. At last, it is not clear how the root-soil slip friction can be associated with the pull-out force and one is left with the open question, how do roots develop supplementary soil strength? On the other hand, tension tests performed in the laboratory directly on individual root fibers can provide a reliable mechanical description of their reaction to tensile stress up to their failure, but still do not help to address the latter question.

A more effective approach to investigate the mechanics of rooted soil is testing its resistance to a controlled shear stress. Indeed, performing direct shear (DS) or triaxial (TX) tests on a fiber-reinforced soil is not novel. A series of DS tests was carried out by [10] on sandy samples with inclusions of synthetic or natural fibers or of metal wires, in order to study their reinforcement effect. In particular, [10] showed that rarely fibers reached their yield stress and failure, as hypothesized in models based on the pull-out approach [11], while their action manifested itself in a non-negligible post-peak strength of the composite material. Fiber-reinforced sandy soils were also tested to triaxial compression by [12] and more recently by [13] who used synthetic or metal short fibers as a reinforcement. By means of TX tests made at high consolidation pressures, [13] showed that the composite material was characterized by values of the friction angle larger than those obtained in absence of fiber inclusions, which increased proportionally to the fiber concentration. Moreover, the results of [13] evidenced that fibers one order of magnitude longer than the size of sand grains supplied their strength more forcefully than shorter fibers.

However, to the knowledge of the authors, a similar experimental approach has never been extended so far to the case of undisturbed rooted soil, namely by using soil samples in which roots were let naturally develop and adapt to the soil structure, exuding natural substances that provide root fibers with adhesion and anchorage. Thus, with the aim of providing a description of the mechanical action of roots, ad hoc moulds were designed and TX tests were made on rooted-soil samples. Moreover, in one series of TX tests, the attempt to reproduce the conditions experienced by a surficial element of soil along a hill slope during an intense storm was made. Besides TX tests, tension tests were also made on individual root fibers to determine their mechanical behaviour under incremental and cyclic stress paths.

2. Methodology and Results

Three series of triaxial tests were made on rooted-soil samples while one series of tests was made on specimens reconstituted by using the same material as the granular matrix of rooted samples. In the following a brief description of the methodology adopted to prepare the rooted specimens is given.

Both soil and plant species were chosen among those commonly used for soil bio-engineering applications in the Liguria region, in particular in the zones that have been recently stricken by several landslides and debris flows. The soil used for the TX tests was picked up from hill fields and consists in clayey sand (SC of the USCS classification). The fine portion was first removed either by dry or wet sieving and grains of diameter $D > 2$ mm were sifted out before preparing the TX test samples, thereby obtaining the grain distribution showed in Figure1a. The removal of the fine part is necessary to guarantee that a purely friction resistance develops at the root-soil interface. It was found that the fine material contained organic matter which cemented in small agglomerates that could be destroyed and removed only by wet sieving. Thus, a weak cohesion was expected for the material sifted with a dry procedure. Anyway, the result of the sieving procedure can be classified as well sorted sand (SW on the USCS classification), the uniformity coefficient being equal to 6.7.

Table 1. Dimensions of roots used for the tension tests. Angular brackets indicate the average operator.

species	$\langle L \rangle$ [mm]	$\langle d \rangle$ [mm]	α [-]	E_2 [MPa]
SJ	49.5	0.57	0.90	340
LI	46.2	0.75	0.82	240
AU	45.9	0.60	0.98	270

Three plant species were considered, namely spartium-junceum (SJ), ligustrum (LI) and arbutus-unedo (AU), which are typical of the Mediterranean scrub. Tension tests on individual root fibers were performed to quantify their tensile strength. The average length and diameter of the fibers considered for the tests are indicated in Table 1 with $\langle L \rangle$ and $\langle d \rangle$, respectively.

Figure1b shows the trend of the Young modulus E as a function of the axial strain ε. Three regions can be identified on the diagram of Figure1b, corresponding to different counteractions of root fibers to increasing deformation stages. The region (I) is characterized by high values of yield stress of the roots, possibly related to the strength enabled by their rigid wood coating, and by nearly hyperbolic decrease of the Young modulus with increasing axial strain. It was observed, by means of incremental load-unload-reload cycles, that in the regions (I) the behaviour of roots was also plastic while in the region (II) it was almost elastic (apart from the hysteresis occurring during unloading-reloading strain-paths). Hence, (I) can be interpreted as a non-linear-elastic plastic region in which the dependence of the Young modulus on $\varepsilon[\%]$ can be approximated by the following expression:

$$E_1 = E_2 \cdot \varepsilon^{-\alpha} \tag{1}$$

where E_2 and α are constants that depend on the species of plants. The values of E_2 and α for the present cases are listed in Table 1. It is interesting to note that $\alpha \sim 1$, varying slightly species by species, while the values of E_1 are in the range of the typical values for wood. For tensile strain larger than 1%, i.e. in the region (II), the Young modulus varies much slower with ε than in the region (I). The average values of the Young modulus in this region, E_2, are indicated in Table 1. Finally, at high deformation stages the wood coating breaks and residual strength can be associated with the core of root fibers. Indeed, in the region (III), up to failure, root fibers experience a high plastic deformation, which reaches values of order $\mathcal{O}(10\%)$. The values of the Young modulus in the regions (II) and (III) as well as their stress path (not shown here) are comparable with those of rubber or other elastomers. Such a detailed description of the mechanical properties of root-fibers was necessary to identify their contribution to the overall strength enabled by the composite material. In the following, a description of the technique adopted to prepare the rooted-soil samples and of the results obtained with the TX tests is given.

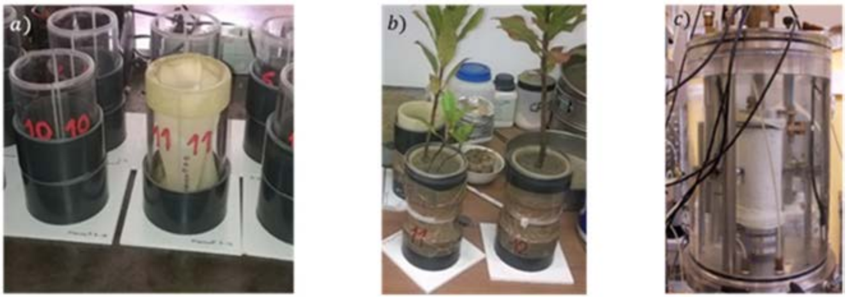

Fig. 2. Pictures of the construction of the moulds (a) and of the preparation of the rooted samples (b), while (c) shows the triaxial cell during the test L1.

In order to let plants develop in their original volume of material, special moulds were designed which could allow an easy assembly and disassembly, guarantee the life of plants by a suitable drainage system as well as avoid the loss or impairment of the granular matrix. Moulds consisted mainly of three pieces: (i) a cylinder of transparent polymethyl-methacrylate (allowing the supervision of the development of roots when approaching the cylinder surface) split vertically into two halves held together by means of a nylon zip tie, (ii) a “bottom cup” equipped with holes of suitable size which allowed the drainage of water preventing the loss of sand, (iii) a coating of dark plastic that was applied externally to the mould in order to limit the direct sun radiation through the transparent cylinder. The presence of a movable bottom cup allowed the installation of the membrane required for TX tests at the stage of preparation of the sample. Fig. 2 shows the moulds before and after the installation of the plants. After the preparation of the samples, plants were let grow for 3 ÷ 5 months in order to make the composite soil-root material more homogeneous and allow the anchoring of roots to the granular matrix. Then, the epigeal part of the plants was removed with a cut at the base of the trunk and samples were mounted on the triaxial cell (see Fig. 2c). It is worthwhile to note that a non-standard sample size (and consequently a special triaxial cell) was used, the height and diameter of which were 14 cm and 7 cm, respectively. A larger size of the samples was required by plants to grow and develop the root system. Both the top and the bottom of the samples were leveled with a layer of uniform coarse sand before each TX test in order to guarantee the uniform diffusion of the vertical compression. In order to reproduce the stress conditions of an element of soil along a hill slope, the samples were consolidated at pressures 40 kPa and 75 kPa, which are relatively small values. Larger consolidation pressures (150 kPa or 300 kPa) were also considered in some cases to investigate the role of roots also in these conditions as well as to outline reliably the failure envelop of the composite material (not presently shown). Table 2 summarises the properties of the granular matrix as well as the volume concentration of roots at the time when the plants where “potted” into the moulds, for the TX tests presently considered. The concentration of roots is comparable with that used for fiber-reinforced soils [13]. In particular, roots were more concentrated for the species LI, which showed also longer and highly branched fibers. The results obtained from standard triaxial compression tests (CIU TX) carried out either on samples rooted with LI or reconstituted without any inclusion, consolidated at 40 kPa and 75 kPa, are shown in Figure3. It is worthwhile to note that significant uncertainties existed on the conditions of the rooted samples both in terms of void ratio (see Table 2) and of the homogeneity of the granular matrix that could be affected physically and chemically by roots.

Table 2. Values of relevant quantities for the TX tests. V_R: volume of roots, $e_{red}^{(m)}$: initial void ratio suitably reduced of the roots volume, G_s: specific gravity, $\gamma_d^{(m)}$: dry specific weight.

test	species	V_R [cm^3]	$e_{red}^{(m)}$	G_s	$\gamma_d^{(m)}$[kN/m^3]
L1	LI	40	1.35	2.75	10.8
L2	LI	25	1.28	2.74	9.44
R1	*recon.*	-	1.15	2.70	12.3
R2	*recon.*	-	1.20	2.70	12.0
M1	LI	25	1.22	2.70	10.6
M2	*recon.*	-	1.21	2.70	12.0

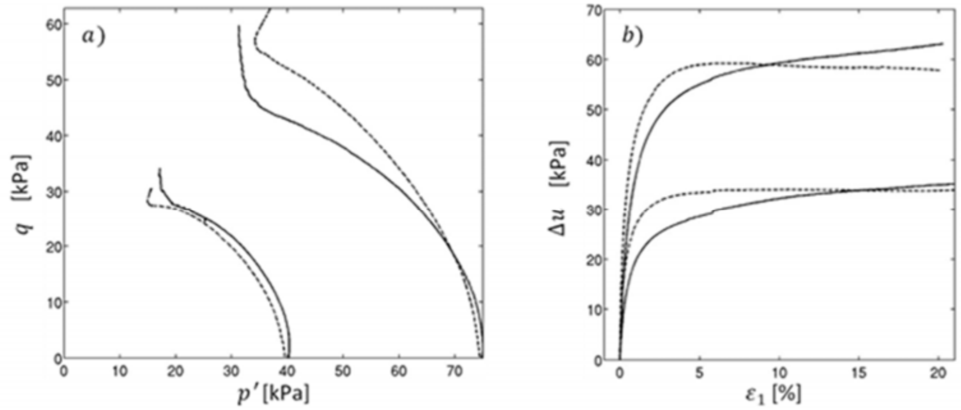

Fig. 3. Diagrams of q (panel a) and Δu (panel b) as functions of p' and ε_1, respectively, for tests L1, L2 (solid lines), R1 and R2 (broken lines).

However, a clear picture of the mechanical action of roots arises from the comparison of tests L1 and L2 with tests R1 and R2 performed on non-rooted samples. Panel a) of Figure 3 shows the trend of the deviatoric stress $q = \sigma_1 - \sigma_3$ as a function of the isotropic effective stress $p' = (\sigma'_1 + 2\sigma'_3)/3$. After the consolidation phase, the samples are brought to failure through constant-strain-rate compression in undrained condition. The pressure Δu which develops as σ_1 increases is shown in Figure 3b as a function of the axial strain ε_1. The path related to rooted samples (L1 and L2) in the $p'q$ −diagram of Figure 3a do not significantly differ from that associated with the non-rooted ones (R1 and R2) until the granular matrix looses its stiffness and tends to dilate. At this stage roots counteract the large increasing radial deformation, ε_3, (the contribution of roots is appreciable only for tensile strain) leading the pore pressure to increase contextually instead of dissipating through the radial expansion (see Fig.3b). As a result, at the final stages of the tests L1 and L2 the deviatoric stress abruptly increases, as shown in Figure 3a, whereas such a behaviour appears significantly damped for the tests R1 and R2 where roots were absent.

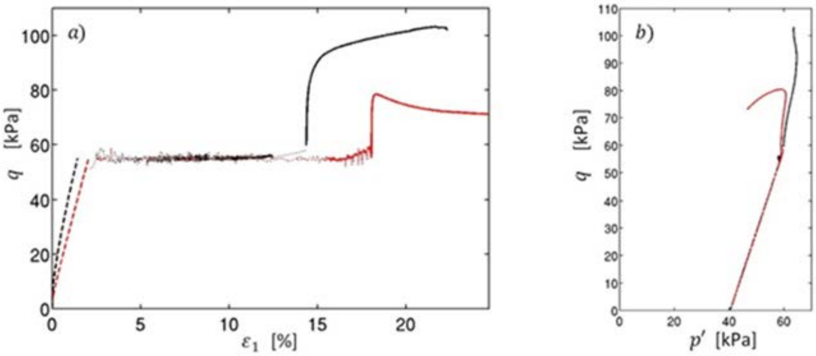

Fig. 4. Diagrams of q as a function of ε_1 (panel a) and p' (panel b) for the tests M1 (black) and M2 (red). Broken, dotted and solid lines correspond to the CID-like pre-load, saturation and final CIU load phases, respectively.

In order to obtain information on the real contribution of roots to the stability and strength of the surficial layers of hill slopes during an intense storm, an ad hoc TX stress path was designed which consisted in three phases: (i) during the first phase a deviatoric stress was progressively applied to the sample in drained condition (CID-like test) until the value of q was equal to ${}^2/_3 q_{cr}$, where q_{cr} is the maximum deviatoric stress supported by a non-rooted sample at failure in undrained conditions. At the end of this pre-load phase, the final stress condition referred to that of an element of soil subject to mobilized shear stress along a stable hill slope. (ii) Then the sample was progressively saturated by applying a back pressure of increasing magnitude, taking care that both p' and q remain unchanged throughout the saturation procedure. (iii) Finally, as the sample was saturated, a CIU test was carried out up to failure. This procedure was applied to a sample rooted with LI and to a reconstituted specimen, which are referred in Table 2 to as tests M1 and M2, respectively. Fig. 4 shows the development of the deviatoric stress as a function of the axial strain (panel a) and of the isotropic stress (panel b) for the tests M1 and M2, while the three phases described above are indicated with broken (i), dotted (ii) and solid (iii) lines. Indeed, a twofold contribution of roots appears: at first, the rooted sample is stiffer than the non-rooted one during the phase (i) and shows a significantly smaller axial strain at the end of the saturation phase. Moreover, as the failure condition is attained during the phase (iii), the deviatoric stress continues to increase monotonically if roots are present, whereas a post-peak decay of q is observed for the case without the root contribution. This is in fair agreement with the results of [10] who observed a similar post-peak behaviour for fiber reinforced samples. Actually, the test M1 was stopped for technical reasons while further strength could have been possibly attained. As previously discussed, the counteraction effect of roots to the radial expansion of the granular matrix can be identified also for the test M1 and is clearly shown by the diagram of Fig. 4b. It is to be mentioned that at the end of each TX test, roots appeared intact, even though the deformation level in the sample was well above the maximum elongation supported by root fibers. This fact suggests that root fibers develop strength with a frictional mode while they slip through the granular matrix rather than purely enabling their tensile strength.

3. On going research

A mechanical interpretation of the reinforcement contribution of roots on the surficial layers of hill slopes has been given on the basis of the results of an experimental investigation. Further tests are necessary to provide quantitative information on the strength of rooted soil and the knowledge of the role of matric suction in unsaturated rooted soil-samples is also required. A mechanical model of the root reinforcement is currently in development.

Acknowledgements

This work has been funded by the PRIN program 2010-2011 prot.2010SWTCKC-008, which is presently acknowledged. We gratefully thank the geotechnics group coordinated by Prof. R. Lancellotta, DISEG, Polytechnic of Turin (Italy) for the fundamental contribution in the experiments (TX tests were performed at DISEG). We also thank Prof. P.M. Capurro and the research group at the material engineering laboratory (DICCA, University of Genoa) who gave us the possibility to make tensile tests on root fibers by means of Zwick/Roell machines.

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