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Experimental Investigation of Root Tensile Strength for Slope Stabilization

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Abstract Bioengineering approaches provide cost-effective ways to protect slopes against surface erosion and shallow mass movements. Indeed, vegetation is an excellent way to control slope erosion and instability of slopes. Plants play an active role both on the surface, protecting and holding soil particles, and at deeper layers, reducing pore pressure and increasing soil shear strength. The use of vegetation is particularly appropriate where soil conservation measures are needed. In the paper, a series of laboratory tests are described, together with the equipment used, to better understand plant root effects on soil shear strength and slope stability. Two species of Mediterranean plants, such as *Asparagus acutifolius* and *Spartium junceum*, were tested in the laboratory. More than 170 tensile tests have been performed on dry and saturated samples. In order to evaluate the effect of soil moisture, most several roots were also tested at different saturation ratios. Laboratory tests also included direct shear tests on root-reinforced and unreinforced samples. Comparison between reinforced and non-reinforced samples confirms the contribution of roots to improve the soil strength.

List of Symbols

α	Angle between the root and the normal to the sliding surface
A_R	Roots area
A	Considered area for stability analysis
A_i	Root area in the class i
β	Angle of the sliding surface to the horizontal
c'	Cohesion
D_b	Root diameter into the stable soil
$\Delta\tau_L$	Increment in strength due to the root
ϕ	Friction angle
F_s	Safety factor with root contribution
F_{s0}	Safety factor without root contribution
γ	Soil unit weight
H_w	Height of the water table
H	Height of the sliding slope
k_h	Horizontal seismic coefficient
k_v	Vertical seismic coefficient
L_b	Average length of the root apparatus into the stable zone
m	Number of classes of roots having a same diameter
n	Number of roots with a same diameter
p_m	Value of distributed load
σ_R	Tensile strength of the root
σ_{Ri}	Average root tensile strength in the class i
τ_L^*	Strength increment due to roots
τ_L	Soil shear strength
τ_{lb}	Average value of the ultimate shear stress at the interface along the root into the stable zone

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Introduction

The interaction between plants and soil has been studied in different research areas. From the engineering point of view, the contribution of plants to the soil improves its mechanical characteristics. The naturalistic approach for slope stabilization on preventing erosion and shallow mass

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movements involves the use of live plants or parts of them (such as seeds, roots, cuttings), alone or in combination with natural inert materials (wood, rocks or soil), artificial biodegradable materials (biomats, geojuta) and non-biodegradable materials (geonetworks, geogrids, geotextiles).

An extensive study of the role that plants play in slope stabilization can be found in specialized papers [1–11].

The focus on the literature in recent decades can be divided into three main topics: theoretical modelling, experimental activity and numerical analysis. For theoretical modelling, an important contribution was given by Wu [10] who described the state of the art on modelling until 2013. Wu divided the theoretical activities into models dedicated to the volume element and finite applications [9, 10, 12]. Further contributions to theoretical modelling were provided by Chen et al. [13] and Schwarz et al. [12]. Experimental activity consists of finite problems [14, 15] and volume element that were carried out by both on-site tests [16, 17] and laboratory tests [17–20]. Experiments confirm the improvement in mechanical characteristics of the soils and the different contribution to the shear resistance offered by the different types of roots [21]. Other experimental activities have been aimed to the characterization of existing models [12, 22–27] or of the individual roots [20, 26, 28–30]. Finally, numerical studies have focused on the analysis of finite problems [31–33]. The synthesis of theoretical modelling introduced by Wu [10] and related to the volume element indicates that the soil–root macroelement can be described with an increased shear strength expressed by the Mohr–Coulomb failure criterion. The increase in resistance is due to an apparent cohesion of the soil in the presence of roots and quantified in an interval between 2 and 15 kPa depending on the species considered and on the tensile strength of the single root. Finally, other authors have performed several numerical simulations. Mickovski et al. [34] simulated, through a 2D and 3D FEM analysis, direct shear tests on rooted and non-rooted soil. Roots have been inserted within the volume of soil modelled at Mohr–Coulomb failure criterion, and the roots were modelled by linear elastic behaviour with an appropriate soil–root interface.

Theoretical Background

One of the most effective models proposed to quantify the effects of root systems on soil stability is based on the limit equilibrium method, assuming that the single roots are cylindrical fibres that extend through the sliding surface. When the soil moves along the sliding plane, shear stress is generated which induces tensile stresses on the deforming roots as shown in Fig. 1. The roots are stretched until the

shear stress mobilized at the root–soil interface and the confining stress are sufficient to prevent the root from pull-out or until the tensile strength of the root is reached. Usually, the maximum tensile strength or pull-out resistance of roots, together with an assessment of root size and distribution, can be used to evaluate the appropriate root reinforcement values to be used in the stability analysis of a slope. Shear strength increment due to roots can be represented as follows (see Fig. 1):

$$\tau^* = \tau + \Delta\tau_L \tag{1}$$

where τ is the soil shear strength and $\Delta\tau$ the increment in strength due to the root, that is (see Fig. 1),

$$\tau = c' + (\sigma - u) \cdot \tan\varphi \tag{2}$$

$$\Delta\tau = \sigma_R \cdot (\sin\alpha + \cos\alpha \cdot \tan\varphi) \tag{3}$$

The factor of safety of an infinite slope, including the stabilizing effect due to the root apparatus, can be expressed as follows (see Fig. 2):

$$F_s = F_{s0} + \frac{(\sin\alpha + \cos\alpha \cdot \tan\varphi) \cdot \sigma_R \cdot A_R}{\gamma \cdot H \cdot \cos\beta \cdot A \cdot [(1 - k_v) \cdot \sin\beta + k_h \cdot \cos\beta]} \tag{4}$$

where F_{s0} is the factor of safety with no stabilizing system, that is,

$$F_{S0} = \frac{c'}{\gamma H \cos\beta[(1 - k_v)\sin\beta + k_h\cos\beta]} + \frac{[(1 - k_v)\cos\beta - k_h\sin\beta]\tan\varphi}{[(1 - k_v)\sin\beta + k_h\cos\beta]} - \frac{\gamma_w H_w \cos\beta\tan\varphi}{\gamma H[(1 - k_v)\sin\beta + k_h\cos\beta]} \tag{5}$$

σ_R the design root tensile stress, ϕ' the friction angle of the soil, k_h and k_v the horizontal and vertical seismic coefficients and A_R the total area of the roots in a sliding base area A; F_{s0} is the factor of safety without taking the
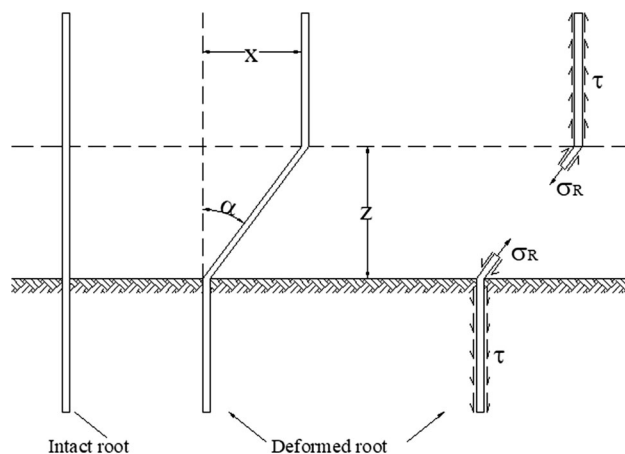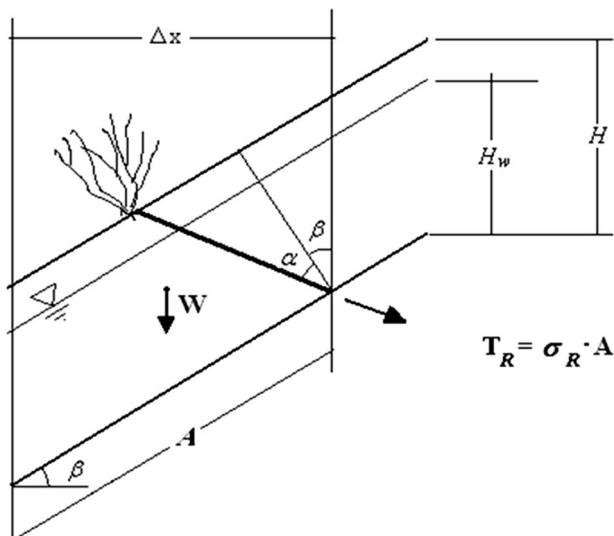

Fig. 1 Model of root-reinforced soil reinforced by perpendicular roots (after Wu [9], modified)
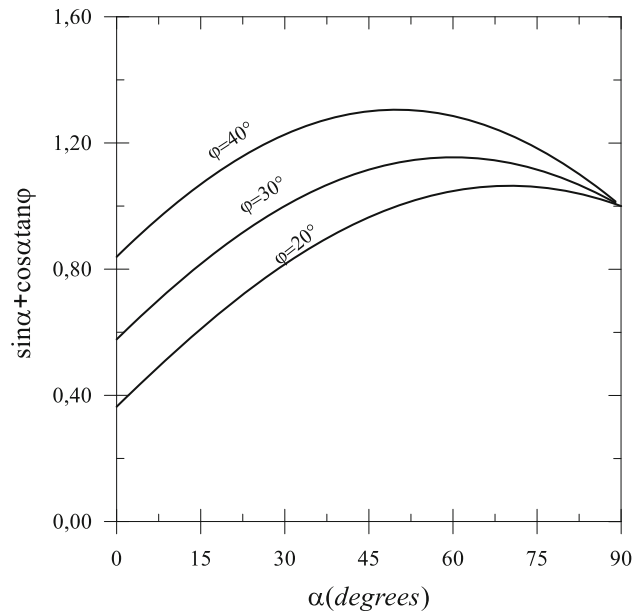
Fig. 2 Scheme of infinite slope with contribution of the tensile force of the root

Fig. 3 Values of function $f(\alpha) = (\sin \alpha + \cos \alpha \cdot \tan \varphi)$ versus α

root stabilizing effects into account. Thus, F_s depends on σ_R and on the root area A_R. From Eq. (5), the root area ratio A_R/A required to obtain a given factor of safety F_s and for a given design root tensile stress σ_R is:
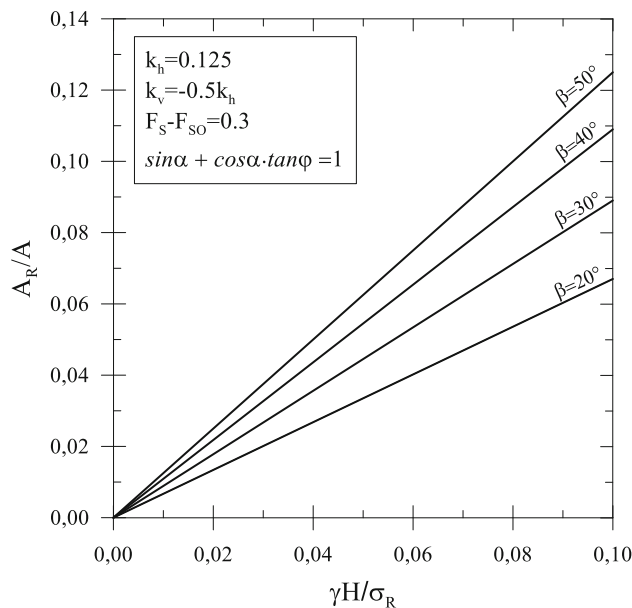
$$\frac{A_R}{A} = (F_s - F_{s0}) \cdot \frac{\gamma \cdot H}{\sigma_R} \cdot \frac{[(1 - k_v) \cdot \sin \beta + k_h \cdot \cos \beta]}{(\sin \alpha + \cos \alpha \cdot \tan \varphi)} \quad (6)$$

For a static analysis of slope stability, the seismic coefficients k_h and k_v must be assumed zero. The determination of the eradicated area ratio is quite complex depending on the value of tensile strength σ_r and the depth of the effective root apparatus. Thus, a preparatory analysis to be done for a given slope is the determination of the areal distribution of roots and their depths. Referring to the angle α, Waldron [35] suggests values in the range 40°–50°. According to Wu [36], α can vary between 45° and 70°. However, the function $f(\alpha)$ has a limited range of values as shown in Fig. 3. Just for an example, Fig. 4 shows the root area ratio derived from Eq. (6), to obtain an increase in safety factor $\Delta F_s = (F_s - F_{s0}) = 0.3$, for a horizontal seismic coefficient $k_h = 0.125$ and for a vertical seismic coefficient $k_v = 0.5 \, k_h$. The root area is determined as a function of the non-dimensional parameter $\gamma H/\sigma_R$.

In order to evaluate an appropriate root area ratio A_R/A to obtain a given factor of safety F_s, the design tensile stress σ_R acting on the roots must be determined. This choice depends on the failure mechanism occurring in the soil–root system. The design tensile stress σ_R must be deduced from the minimum ultimate value determined among all the possible failure mechanisms, that is,

Fig. 4 Root area ratio required to increase the safety factor of an infinite slope

1. Ultimate limit state for achieved tensile strength in the root;
2. Ultimate limit state for achieved pull-out of the root;
3. Ultimate limit state for the achieved failure of the soil arching between two adjacent roots.

In this study, we refer only to the ultimate state achieved for the reached tensile strength in the root and whose design values can be determined by experimental tests.

Laboratory Tests

The experimental activity carried out in the laboratory represents a further development of previous work son the tensile strength of roots of native Mediterranean plants [37, 38]. Here, the presented tests are much more numerous and were performed at different saturation ratios of the root to evaluate the contribution to tensile strength of the water content inside the root. Root samples of two typical Mediterranean plant species were collected from the sites located near Catania and Ragusa in Sicily. Different sets of plants have been used: *Black Asparagus* from Motta S. Anastasia (Catania), Mirabella Imbaccari (Enna) and Cava d'Ispica (Ragusa) and *Spartium junceum* from Motta S. Anastasia (Fig. 5).

These plants have been removed with their root balls from their sites. The *Spartium junceum* roots are usually deeper than the *Asparagus acutifolius* ones. Indeed, roots of *Asparagus* samples were taken from a depth of 0.20–0.40 m (Fig. 6).

The *Spartium junceum* roots were taken at a depth of about 0.50–1.50 m from the ground surface. The experimental activity consisted in the evaluation of tensile strength of 128 root samples of *Asparagus acutifolius* and 44 roots samples of *Spartium junceum*. Qualitative information about the increase in soil shear strength due to root reinforcement was achieved by performing a series of direct shear tests at the laboratory of the University of Catania.

Tensile Tests

A root tensile test is used to estimate the mechanical properties of a root in terms of maximum tensile strength and elastic modulus. Tensile tests are carried out in the laboratory, usually using a universal testing machine [26, 28, 32, 39]. A testing machine has a stationary part and a moving part that pulls the root. The tensile force is recorded with a load cell usually coupled to a displacement sensor. Different solutions were used by Operstein and Frydman [26] who used a simple dead-load system. The

Fig. 5 Plants used for experimental investigation: **a** *Asparagus acutifolius*; **b** *Spartium junceum*
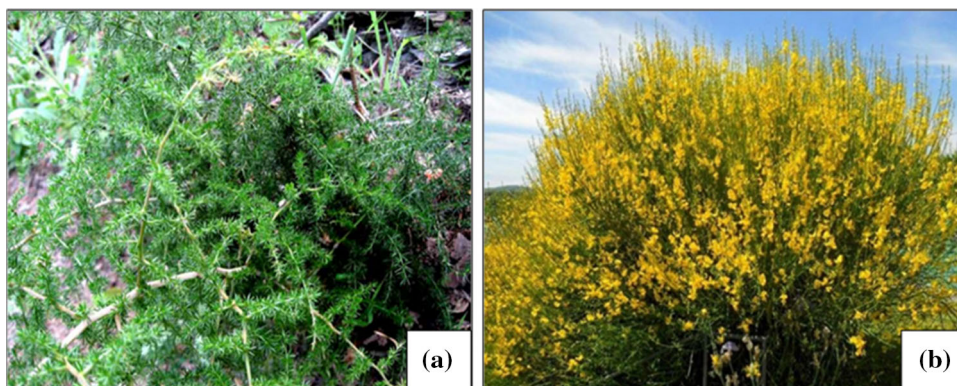
Fig. 6 Root apparatus of *Asparagus acutifolius*

quality of results from tensile tests depends on a number of factors, some related to the experimental set-up of the device such as clamping and pull-out speed and others to the root specimen, e.g. diameter, length and moisture, that can affect data significantly.

The experiment consisted in the evaluation of the root tensile strength of 172 samples, that is, 21 samples of *Asparagus acutifolius* from Mirabella Imbaccari, three root samples of *Asparagus acutifolius* from Motta S. Anastasia, 104 root samples of *Asparagus acutifolius* from Cava d'Ispica and 44 roots of *Spartium junceum* from Motta S. Anastasia (Sicily). The root samples were classified, according to their diameter, into five groups for the *Asparagus* and four groups for the *Spartium* (Fig. 7 and Tables 1, 2).

In order to evaluate the effect of moisture content on the tensile strength of roots [38], in most samples imbibition
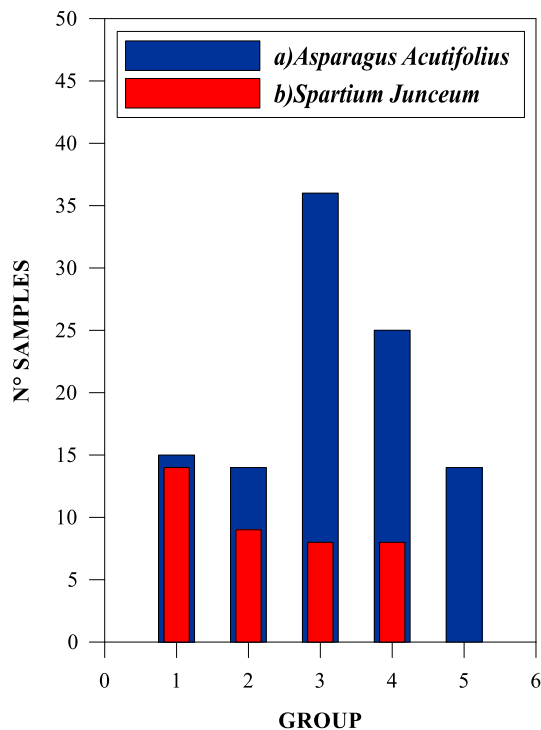

Fig. 7 Classification of plant roots investigated

Table 1 Root groups for *Asparagus acutifolius* classified by diameter

Group	N°	D (mm)
1	19	$2.5 < d \leq 3.0$
2	18	$3.0 < d \leq 3.5$
3	43	$3.5 < d \leq 4.0$
4	28	$4.0 < d \leq 4.5$
5	20	$d > 4.5$

Table 2 Root groups for *Spartium junceum* classified by diameter

Group	N°	D (mm)
1	14	$1.0 < d \leq 2.0$
2	10	$2.0 < d \leq 3.0$
3	11	$3.0 < d \leq 5.0$
4	9	$d > 5.0$

and drying tests were performed. Typical examples of imbibition and drying curves are shown in Fig. 8. Imbibition was obtained by immersing the roots in water and measuring the weight variation at fixed time intervals until the roots did not absorb water anymore. The roots were dried using an oven.

The device utilized to measure tensile strength of samples combines three functions: tensile force generation up to 40 kN, load and displacement measuring and data acquisition. The ends of the roots were clamped using cork and polystyrene as shown in Fig. 9. This clamping system did not affect the outcome of the test, since the root failure occurred in the middle of their length, distant from the clamps (Fig. 10).

Results of tensile tests for Asparagus samples are shown in Fig. 11. The failure load is plotted versus the diameter at various saturation ratios ranging from 100 to 25% (Fig. 11a–c). The tensile strength versus the root diameter at saturation ratios S_r from 100 to 25% is plotted in Fig. 11d–f. The failure load obviously increases with the root diameter, but the results indicated that the tensile strength at failure σ_R roughly decreases with the increase in the root diameter. A same trend was observed for the *Spartium junceum* tensile tests, as shown in Fig. 12. This behaviour could be explained if one assumes that the tensile strength of the root cuticle is greater than the tensile strength of the internal flesh, so that the less is the diameter of the root, the greater is the relative contribution of the cuticle to the root tensile strength. This phenomenon can be considered similar to the specific surface concept. It was found that the tensile strength of Asparagus root increases for saturation ratio ranging from 50 to 100% while it decreases in dry roots. Even for the broom samples, it was found that dry roots were weaker than roots with a saturation ratio ranging from 50 to 100%. Finally, all the results were put together, regardless of the saturation ratio, as illustrated in Fig. 13 which shows the root tensile strength for both the species of plants. There are significant differences in the tensile strength of the two species analysed. Generally speaking, it has been found that the tensile strength of *Spartium junceum* was much greater than the tensile strength of *Asparagus*.

(a)

(b)
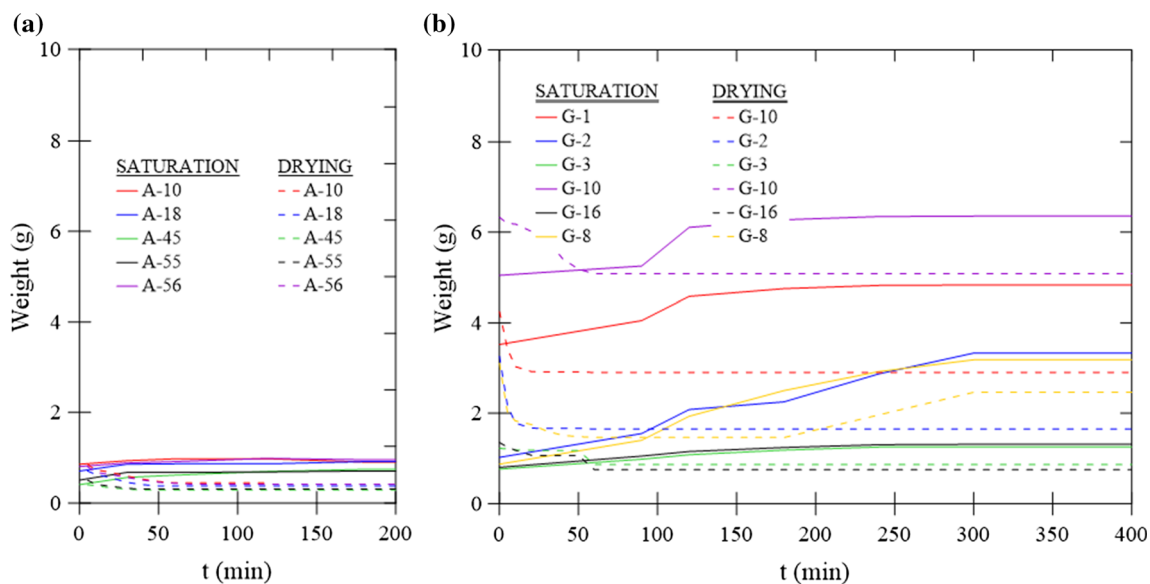
Fig. 8 Saturation and drying curves: **a** *Asparagus acutifolius*; **b** *Spartium junceum*

Fig. 9 Root samples utilized for tensile tests and equipped with cork clamps

Direct Shear Tests

The behaviour of a rooted soil is similar to that of a composite material, consisting of a matrix in which elastic fibres are inserted. A series of direct shear tests were carried out in order to verify the contribution of plant roots on soil shear strength. Reinforcements were realized with Asparagus roots. The Kaolin *Speswhite* and the *Montelupo* clay were used in the tests. Shear tests were carried out on 60 mm × 60 mm reconstituted samples. Tests were performed on both unreinforced and reinforced soil. For the reinforced Kaolin samples, a single root was disposed as shown in Fig. 14a, while for reinforced Montelupo clay samples five roots were disposed as shown in Fig. 14b.
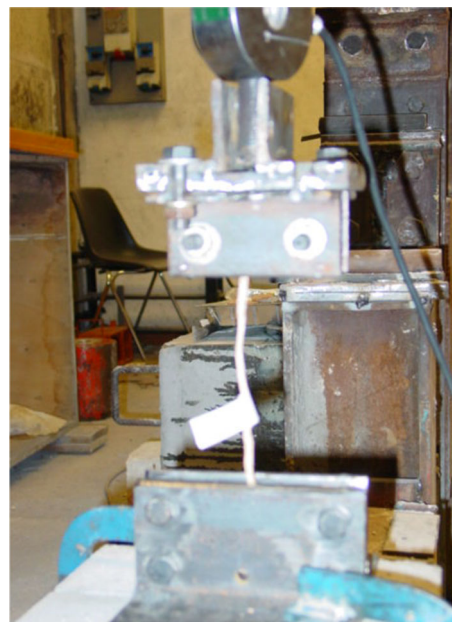

Fig. 10 Details of root connection with the clamp to driving system

The contribution of reinforcing roots is clearly evidenced by the comparison between reinforced and unreinforced soil tests. Shear stress–displacements curves for the Kaolin Speswhite are plotted in Fig. 15. Figure 15a concerns the reinforced soil with a single root; Fig. 15b concerns the unreinforced soil. In the reinforced soil, an increase of about 30% in strength was observed. Shear stress–displacement curves of the Montelupo clay are plotted in Fig. 16. Figure 16a concerns the reinforced soil with five roots; Fig. 16b concerns the unreinforced soil. Despite the major number of the roots, the increase in
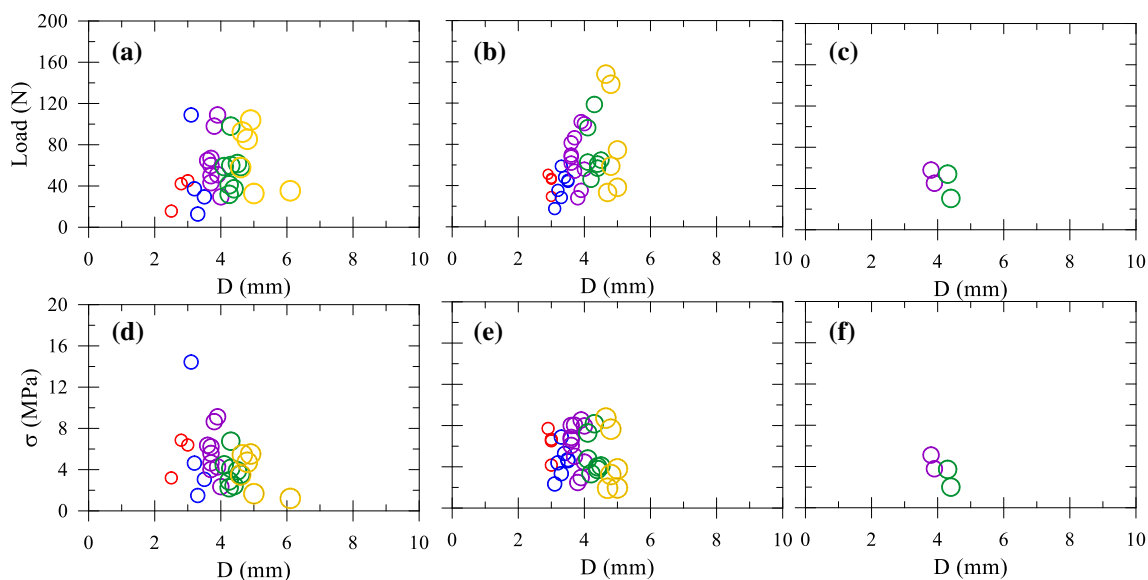
Fig. 11 Results obtained from *Asparagus acutifolius* samples: **a** failure load versus root diameter at saturation = 100%; **b** failure load versus root diameter at saturation = 50%; **c** failure load versus root diameter at saturation = 25%; **d** tensile strength versus root diameter at saturation = 100%; **e** tensile strength versus root diameter at saturation = 50%; **f** tensile strength versus root diameter at saturation = 25%
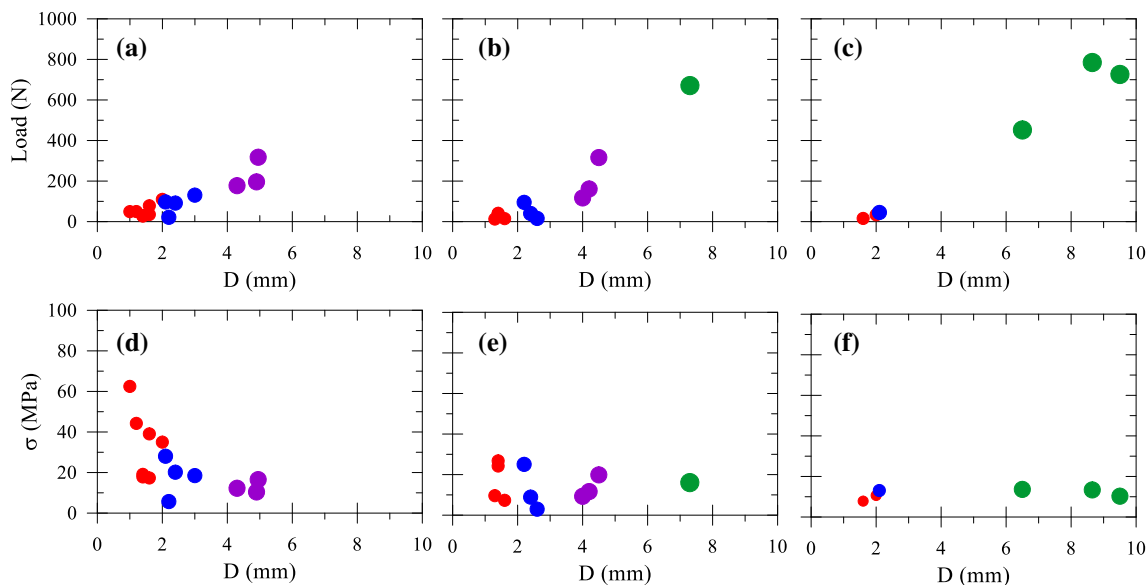

Fig. 12 Results obtained from *Spartium junceum* samples: **a** failure load versus root diameter saturation = 100%; **b** failure load versus root diameter saturation = 50%; **c** failure load versus root diameter saturation = 0%; **d** tensile strength versus root diameter saturation = 100%; **e** tensile strength versus root diameter saturation = 50%; **f** tensile strength versus root diameter saturation = 0%

soil shear strength in the reinforced soil was not proportional to the number of roots. The increase in shear strength was also dependent on the vertical stress applied since this one increases the pull-out resistance. Indeed, because of the limited thickness of the soil samples, in such tests, the ultimate shear strength was conditioned by the root pull-out resistance rather than the root tensile strength. A typical failure in reinforced samples is shown in Fig. 17.

Finally, Fig. 18a, b shows the failure envelopes for both unreinforced and reinforced soil. The contribution of root manifests in some apparent cohesion and in a slight increase in friction angle. The results show an improvement in the shear strength parameters in both tests.

Fig. 13 Comparison between the results of first phase and the results of second phase: **a** *Asparagus acutifolius*; **b** *Spartium junceum*
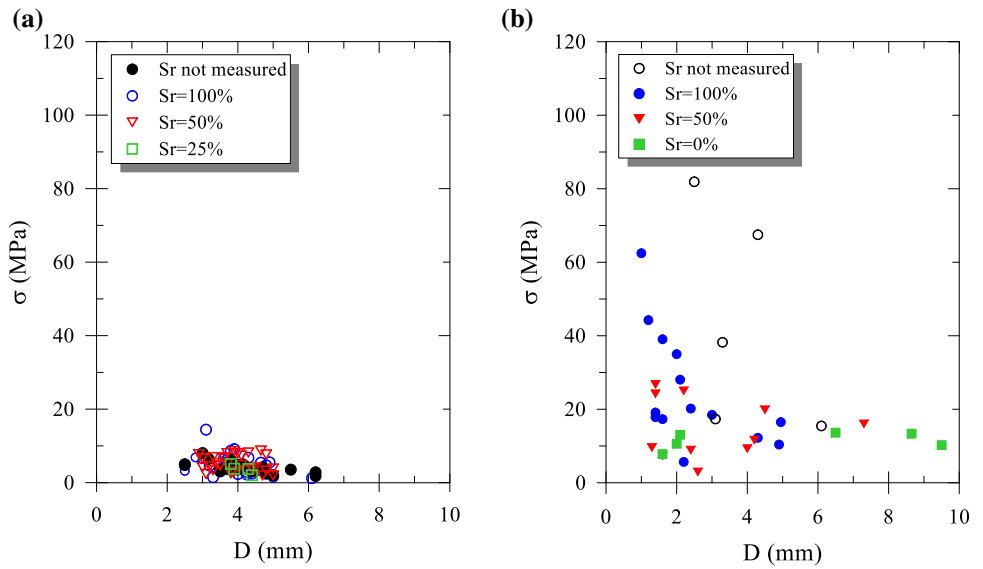
Fig. 14 Scheme of sample: **a** Kaolin sample reinforced with 1 root; **b** Montelupo clay sample reinforced with five roots
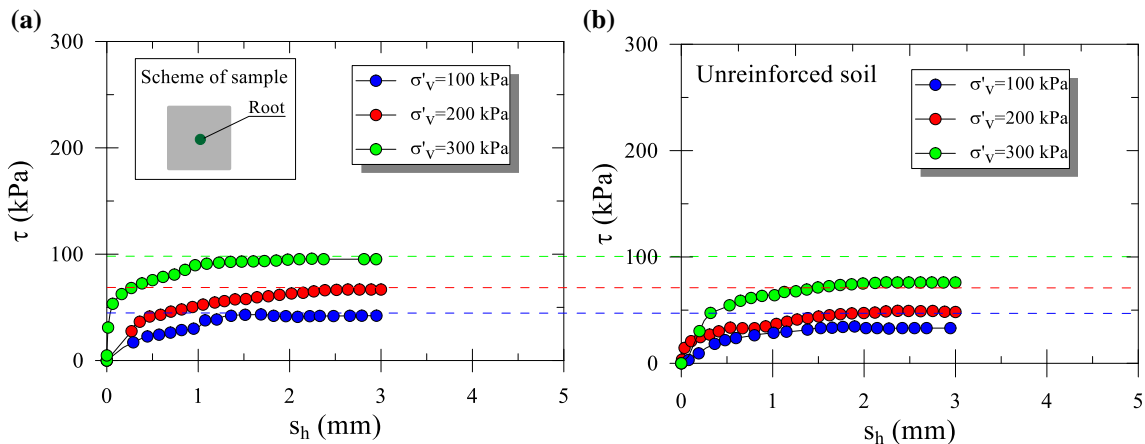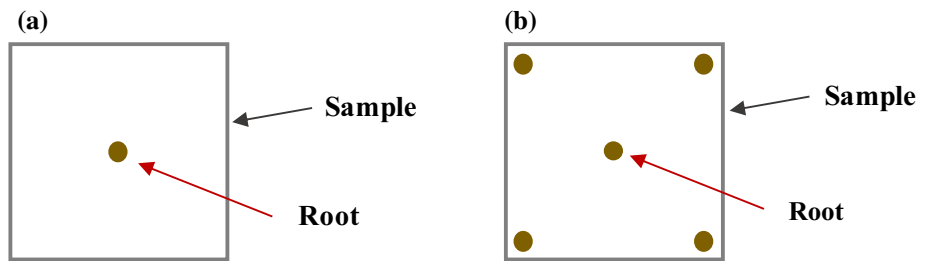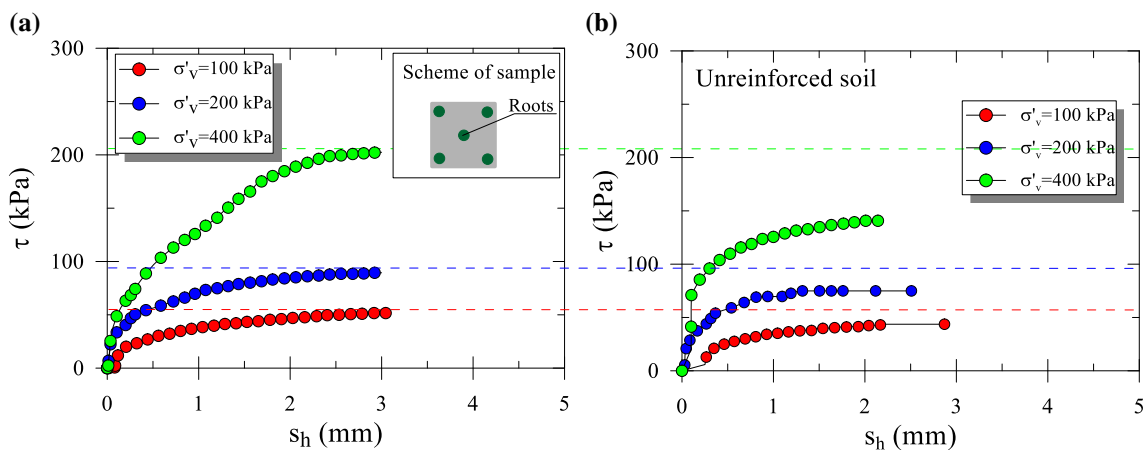

Fig. 15 Direct shear test results for the "Kaolin Speswhite" sample: **a** shear stress versus horizontal displacement curves at different vertical stresses for sample with root; **b** shear stress versus horizontal displacement curves at different vertical stresses for sample without root

Conclusions

An experimental laboratory investigation about the tensile strength of the roots of two species of Mediterranean plants has been presented. The main findings can be used as a reference for further studies and are summarized as follows:

- In the tensile tests that were carried out, the failure load increased with the root diameter; however, the root diameter has a significant effect on tensile strength σ_R which tends to decrease as the diameter increases. This behaviour can be explained if one considers that the tensile strength of the root cuticle is greater than the tensile strength of the internal flesh, so that the less the

Fig. 16 Direct shear test results for the "Montelupo clay" sample: **a** shear stress versus horizontal displacement curves at different vertical stresses for sample with roots; **b** shear stress versus horizontal displacement curves at different vertical stresses for sample without root

Fig. 17 Typical failure in samples of reinforced Kaolin
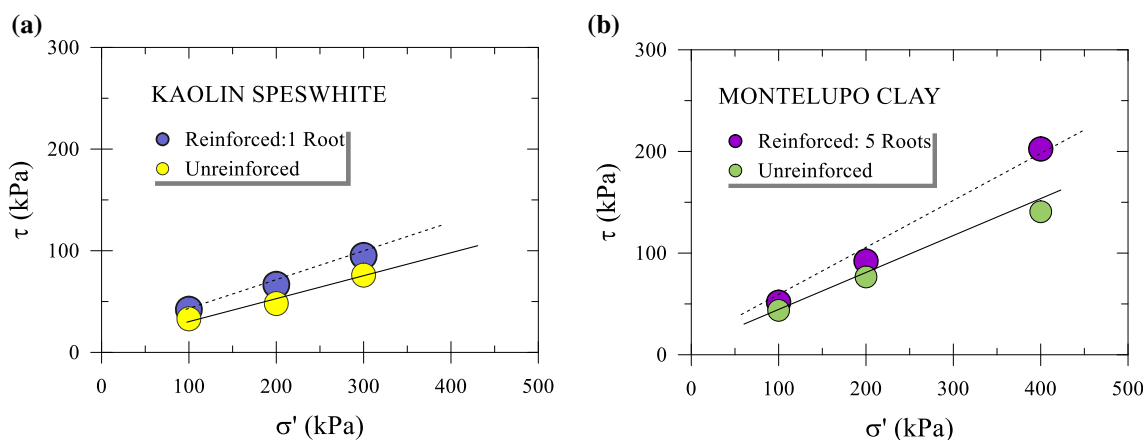
Fig. 18 Shear strength envelopes: **a** Kaolin Speswhite; **b** Montelupo clay

diameter of the root, the greater the relative contribution of the cuticle to the root tensile strength;

- It was found that the tensile strength of Asparagus roots roughly increases for saturation ratios ranging from 50 to 100%, while the tensile resistance decreases in dry roots. Even for the brooms it was found that dry roots were weaker than roots with a saturation ratio from 50 to 100%;

- The kind of species may have a great effect on tensile strength of roots. Significant differences were found in tensile strength between the two species analysed. The tensile strength of *Spartium junceum* was much greater than the tensile strength of the *Asparagus*;

- A verification of the role of the root in the increase in soil shear strength was also achieved with direct shear tests by comparing the resistance of unreinforced and

root-reinforced samples. The tests performed on the direct shear box confirm the contribution to soil shear strength of root reinforcement. An increase of about 30% of soil shear strength was found, but the increase was not proportional to the number of roots utilized as reinforcements. It has been observed that, due to the small size of the soil samples, the ultimate shear strength was achieved with a pull-out mechanism of failure, so that the increase in shear strength was also dependent on the applied confining pressure. In this case, the increase in shear strength can be taken into account by an apparent cohesion and a greater friction angle.

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