Soil bio-engineering techniques to protect slopes and prevent shallow landslides

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Summary

Soil bio-engineering techniques consist in the use of plants, often combined with wooden structures, for the protection and reinforcement of soil and contextually for the re-naturalization of anthropic areas. They are often possibly adopted in place of traditional geo-engineering works because of ecological and economic benefits although a deeper knowledge of their actual mechanical action is requested by practitioners. The present contribution was developed in the framework of a research project focused on the mitigation of landslide risk and is divided into two parts. After a brief overview of the most common soil bio-engineering practices, the results of experiments that were performed on plant roots and on rooted soil samples are shown and discussed in the first part of the paper. Indeed, the role of roots, which is fundamental in almost all soil bio-engineering techniques, is emphasized by the practice of re-vegetation. Presently, the mechanical action of roots on a saturated sandy soil undergoing shear strain, is identified at the scale of volume element. Advantages and limits of Wu and Waldron's model, which is frequently used to estimate the contribution of roots to the soil shear strength, are also investigated. In the second part of the paper, a general description of live wooden cribwalls is given which is aimed at making practitioner aware of the effectiveness of this technique to retain cuts a few meters high and guarantee the stability of slopes. The mechanical contribution of plants, that progressively enhance the performance of cribwalls, is shown in terms of increments of the safety factor of the structure.

1. Introduction

Soil bio-engineering is a technical-scientific discipline that makes use of live plants, preferably native, as a sort of structural material. Indeed, the aims of protection and consolidation of soil as well as of stabilization and re-naturalization of slopes are pursued by means of the installation of plants, often combined with inert materials such as wood, stones and metal. The most frequent interventions consist of seeding, slope plantings, brush layerings, slope fascines, planted pole walls, live slope grids, live wooden cribwalls, vegetated stone walls and vegetated gabions. These techniques are used since ancient times. For instance, in China in 28 B.C., the stabilization of dams and river banks by means of baskets of willow or bamboo is documented, while in Europe the Celts wove willow branches to make fences for military purposes and the Romans left several treatises on soil classification and the use of willow cuttings. Moreover, the stabilizing effect of roots on the soil was recognized, as evidenced by Leonardo da Vinci in reference to river banks. Nowadays, soil bio-engineering techniques are mostly adopted in mountainous regions, while elsewhere the use of building materials, like steel and concrete, is more common. From the early works of Kruedener in the 1930s up to the more recent contributions of Schiechtl (*e.g.* Schiechtl, 1991; Schiechtl and Stern, 1996), soil bio-engineering found first wide diffusion, in the professional field, in Germany, Austria and Switzerland, then calling the attention of other countries. For instance, in Italy, it is worthwhile to mention the pioneering contribution of Florineth [Florineth, 1973; Florineth, 2007; Bischetti *et al.*, 2014]. Indeed, in Italy, soil bio-engineering practices were recognized in 1978 with the creation of the "Azienda Speciale Bacini Montani dell'Alto Adige" and formally in 1989 with the creation of the Italian association "Associazione Italiana per l'Ingegneria Naturalistica" (A.I.P.I.N.).

The soil bio-engineering practices are useful tools for the mitigation of the hydrogeological risk in situations where environment, ecosystem and landscape should be preserved or restored. Indeed, among the advantages of soil bio-engineering techniques, we mention the following ones:

- the presence of vegetation plays both mechanical and hydrological roles since it contributes to the stabilization of soil and to the protection against rainfalls, reducing soil erosion and enhancing the drainage of water;
- in terms of ecology, in intensively used and degraded sites, revegetation can help to recover a

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natural environment (especially by using native species);
- the landscape is aesthetically improved.

It can be pointed out that soil bio-engineering works represent possible alternatives to "conventional" retaining structures because they can easily adapt to hill-slope displacements. They are also often less expensive and easier to be built especially in sites of limited accessibility. Furthermore, if plants are suited to the site, properly planted and maintenance is appropriate, the functionality of works can increase over time as the plants grow up.

However, limits of soil bio-engineering techniques exist with respect, for example, to concrete structures. First, the effects of soil bio-engineering countermeasures vanish at relatively small depth below the slope surface. Then, they are less effective in the short-term because plants, need months to develop deep roots. Moreover, the use of plants with technical and construction purposes requires a regular maintenance and implies that the effectiveness of soil bio-engineering works is strongly affected by climatic and geographical conditions. Furthermore, the design parameters available for natural materials (e.g., cuttings, wood) are more difficult to be quantified than those of conventional materials. Finally, because of its relatively recent formalization and of the uncertainties in the design parameters, the constructive procedures of soil bio-engineering works are currently neither well defined nor standardized. Therefore, soil bio-engineering countermeasures are often realized without performing a proper sizing, ignoring or not fully satisfying the necessary design analyses.

Nevertheless, it is recognised that soil bio-engineering works can be considered an alternative to traditional ones to reinforce and stabilize slopes, in particular to prevent shallow failures.

It is well known that the techniques aimed at stabilizing slopes can be generally classified in the following four groups:

1) flattering and other measures which modify the geometry of the slope to obtain a new configuration that guarantees adequate stability conditions;
2) works that protect slopes from agents which may affect the slope stability conditions (*e.g.* preventing the erosion);
3) interventions that improve the soil/rock mechanical behaviour, by supplying a further contribution to the stabilizing forces;
4) structural works (internal or external) that provide supplementary stabilizing forces.

A classification of both geotechnical and soil bio-engineering countermeasures, on the basis of these four groups, is reported in table I [BOVOLENTA and PASSALACQUA, 2014]. Among the soil bio-engineering techniques, revegetation and live wooden cribwall techniques are widely used, even though design criteria are almost committed to the experience of practitioners.

Revegetation, which includes both seeding and sowing or planting of cuttings, is aimed at providing slopes with a turf that contributes to protect and reinforce the soil with the aboveground and belowground parts of plants, respectively.

Live wooden cribwalls (LWCs) are particularly effective to retain cuts. The vegetal cuttings, inserted into the structure, enhance, with their roots, the overall performance of the work.

The present contribution is aimed at improving our insight on the effectiveness of revegetation and LWCs. In particular, laboratory tests were carried out to identify and quantify the mechanical action of roots in vegetated slopes, which are described in the following section. Then, a general discussion on the effectiveness of LWCs and on the effects of plants on the performance of the structure is provided, along with some practical suggestions on the preliminary sizing.

Finally, in the conclusive section, the main results are recalled and summarised.

2. Revegetation

The use of plants to provide soil with additional shear strength is not necessarily associated with the use of complementary frameworks. Indeed, some species of plants develop roots sufficiently dense and deep to supply a significant support to the soil. In fact, the revegetation of slopes by means of hydroseeding and the installation of plants is a common soil bio-engineering practice. Revegetation can be adopted both to restore disturbed soils, guaranteeing a natural appearance, and to reinforce the deeply remixed soil resulting from traditional geotechnical or soil bio-engineering works. The effectiveness of revegetation is strictly related to the proper selection of plant species. For instance, even though trees are able to develop deep roots (*e.g. Pinus Halepensis* for the Mediterranean environments or *Quercus Cerris* and *Quercus Ilex* for Italian mountainous lands) thereby sustaining relatively thick layers of soil (up to ~3 m), the time they require to develop such a root system exceeds a decade, which is too long to prevent the seasonal erosion of soil. Actually, trees are typically not used for the slope revegetation because of their weight and height. In fact, they would turn into a significant additional load and transfer the wind actions to the ground. Moreover, trees produce cracks into the soil, allowing water infiltration. For these reasons, herbaceous and, preferably, shrub species are commonly adopted for revegetation. They can be used to provide rapidly the protection of slopes from erosion and shallow failures because

their roots grow several centimetres in a few months. Besides the geometrical and mechanical properties of roots, also biological factors, like the effect of the adhesive substances exuded by roots, should be considered to understand the effectiveness of revegetation. Indeed, the use of native species is always advisable since introducing foreign species could disturb the equilibrium of the ecosystem and modify the landscape *(e.g.* the infesting North American *Robinia Pseudoacacia* that was introduced to reinforce river banks). Nonetheless, certain tropical herbs can develop such a deep and dense root system that it can be tempting to explore the possibility of using foreign species for geotechnical purposes, *e.g.* see CECCONI *et al.* [2012].

Although at the boundary-problem scale and at the micro-scale the rooted soil can appear heterogeneous, at the volume-element scale the mixture of soil and root shows homogeneity features which suggest the possibility to develop a constitutive model for the composite material accounting for the root-soil interaction. Unfortunately, the combination of structural, biological and climatic factors makes the problem of quantifying the actual mechanical action of roots on the soil extremely difficult to be tackled. Even disregarding the biological issues, models that can be found into the literature are based on hypotheses difficult to be verified in the field. A simple approach to model roots consists in assuming that they are flexible elements capable of supplying the soil shear strength with an additional contribution, independent of the stress conditions, as they are involved in a shear deformation. In other words, the soil is subject to a shear stress reduced by the counteraction of root filaments which mobilize the tensile stress by virtue of their ductility without any effect on the soil friction angle. An increase of the number of root fibers manifests itself in a proportional upwards shift of the failure envelope in the σ'-τ plane, σ' and τ denoting the normal and shear effective stresses, respectively. This model shows a fair agreement with the experimental results of GRAY and OHASHI [1983] and of ZHANG *et al.* [2010] for normal stresses larger than ~100 kPa. However, for the values of σ' smaller than 100 kPa, which are however typical stress conditions of vegetated soil along a slope, the model gives poor results. Hereinafter, let this kind of models be referred to as "root-cohesion models". For instance, the celebrated models of WU [1976] and WALDRON [1977] (often referred to as Wu and Waldron's model), that, after several modifications, is still frequently used to model the contribution of roots to the soil shear strength, assume that roots are elastic fibers crossing perpendicularly the shear band and do not slip during the shear deformation, mobilizing their tensile stress until their yield stress is reached and then break. In particular, [WU *et al.*,1979] further simplified Waldron's approach assuming that the yield stress was simultaneously attained by roots independently of the magnitude of their strain. The rooted area ratio (RAR), namely the fraction of the shear surface occupied by roots per unit area, which is a fundamental parameter of these models, is difficult to be estimated also in the laboratory since it depends both on the "architecture" of roots and on the position of the shear surface (which are usually unknown).

Such an approach does not account for the fact that the friction angle of a cohesionless soil can benefit from the presence of natural or synthetic fibers, in particular at low confinement pressures [GRAY and OHASHI, 1983; MAHER and GRAY, 1990; MICHALOWSKI and ZHAO, 1996; MICHALOWSKI, 1997; ZHANG *et al.*, 2010]. Also the model of WALDRON and DAKESSIAN [1981], in which the hypothesis of no-slip at the root-soil interface was relaxed, or the most recent models, like the fiber bundle model used by POLLEN and SIMON [2005] and the root bundle model formulated by COHEN *et al.* [2011], which assume the non-simultaneous failure of root filaments, do not account for the effect of roots on the soil friction angle. Hence, a constitutive model for the rooted soil should take into account both the additional constant contribution to the shear strength, due to the confinement effect of roots on the soil, and the improvement of the soil frictional properties resulting from the soil-root interaction at the micro scale (*e.g.* at the interface between root filaments and soil grains).

At the present stage, a better understanding of the mechanism of action of roots on the soil is required.

A brief description of Wu and Waldron's model is provided in the following section. Then, the main results of a specific laboratory investigation, recently performed by the authors, are discussed.

2.1. Root-cohesion models: advantages and limits

As previously quoted, "root-cohesion models" are based on the assumption that the increase of soil strength is offered by the presence of roots in terms of a cohesive-like contribution. Such a soil-root model was originally developed by WU [1976] and WALDRON [1977] in which roots were treated as flexible, elastic reinforcing elements. Starting from the Coulomb equation, with the effective cohesion and the angle of internal friction associated with the native soil, several assumptions were made in order to account for the presence of roots: i) roots extend perpendicularly across a shearing zone of finite and constant thickness (also during the shearing); ii) roots are flexible and linearly elastic; iii) the soil friction angle is unaffected by roots; iv) the root stressed length is approximately the same as the unstressed one, due to the small extent of mobilized tensile strains.

Thus, the modified Coulomb equation reads:

$$\tau_f = c' + \sigma' \tan\varphi' + \Delta\tau, \quad (1)$$

in which $\Delta\tau$ represents the contribution of roots:

$$\Delta\tau = \delta \cdot T_R \cdot \frac{A_R}{A_S} \quad (2)$$

where δ denotes a parameter which depends on the soil friction angle and the average deflection angle of the roots inside the sheared zone, T_R is the estimate of the maximum tensile stress developed in the roots at any given shear displacement and A_R/A_S is the ratio of the total root cross section area at the shear plane to the total soil shearing cross section area (often indicated as RAR).

After the introduction of this semi-empirical root-model in its original form, the model was extended to accommodate a number of experimental evidences and results, for instance to account for the possibility that roots may not only stretch but also slip through the soil or break, (*e.g.* see WU *et al.*,1979; WALDRON and DAKESSIAN, 1981; WU *et al.*,1988). For practical purposes the parameter δ can be assumed as large as 1.2. The rooted area ratio (RAR) is difficult to be estimated since it depends both on the "architecture" of roots (which in turn is influenced by site conditions and by the type and age of plants) as well as on the position of the shear band. Nevertheless, several experimental determination of the values of T_R and RAR can be found into the literature *(e.g.* see WU *et al.*, 2013 or CAZZUFFI *et al.*, 2014, as a review). The tensile properties of the roots used for the present investigation were also determined experimentally and are shown in the next section. The increase of shear strength of rooted soil, $\Delta\tau$, obtained by this kind of models typically falls in the range $2 \div 10$ kN/m^2.

Since Wu and Waldron's model is often used in limit equilibrium analyses for assessing the safety factor of a slope, *e.g.* BOVOLENTA and DALERCI, [2011], an exploration of the parameter space is proposed in the following in order to highlight the influence of roots (modelled as suggested by equations (1) and (2)) on the slope safety factor, bearing in mind that this approach can be adopted only to obtain preliminary indications on potential shallow landslides.

The parameter analysis is performed in the ideal (but frequently adopted in this context) case of a slope of infinite extension, inclined of angle β over the horizontal plane, with a potential failure plane located at distance H from the slope surface. The seepage is assumed to be parallel to the slope and the water table is located at distance H_w above the potential failure plane.

The soil was assumed either dry or fully saturated and the values of the parameters listed in the following were considered:

H = 1, 2, 3 m
$m=H_w/H$ = 0, 0.5, 1.0
β = 20°, 30°
γ = 18 kN/m^3 (soil unit weight)
φ' = 27°, 30°, 35°
$c = c' + \Delta\tau = 0 \div 15$ kN/m^2 ("total cohesion", sum of effective cohesion and resistance provided by the roots).

The values of the safety factors are calculated as a function of the "geometric" parameter ($\tan\varphi'/\tan\beta$) by varying the values of the ratio $m=H_w/H$ and of the parameter c/H. In particular, figure 1 emphasizes the effect of c/H on the safety factor.

It appears that the reinforcement of roots, modelled by a root-cohesion model, is significant for deeply-rooted soil if the ratio c/H is relatively high (that is c = 5 kN/m^2, H = 1 m or c = 10 kN/m^2, H = 3 m), while, for lower values of c/H (e.g. $c/H = 2 \div 3$ kPa/m) an increase of the safety factor can be appreciated only if the water table does not rise within the potential unstable layer ($m \leq 0.5$).

Being aware that a more detailed analysis (e.g. including in the infinite slope model also an apparent cohesion due to unsaturated soil), would lead to more significant results, it is worth to note that the simplified analysis here reported has the sole purpose of showing, in a schematic way, advantages and the shortcomings of a possible wrong use of root-soil interaction models based on an additional contribution to cohesion.

In fact, despite the remarkable simplicity of calculation, practitioners should bear in mind the strong assumptions at the base of the model and the difficulties of a proper choice of the RAR and T_R values. Indeed, it is known that Wu and Waldron's model can lead to an overestimation of the contribution to the shear strength associated with roots. The main causes of the overestimation are two:

(i) the maximum contribution of root filaments is attained for displacements of a few centimetres which could be larger than those observed in the field. Therefore, the potential shear strength of roots is rarely fully mobilized.
(ii) The hypothesis that root filaments break simultaneously is not realistic since the progressive failure of individual roots is associated with its shape, thickness, length, degree of branching, as well as material properties and local characteristic of soil.

In order to get round these inconveniences and all the uncertainties previously reported, a reduction coefficient ranging between 0.2 and 0.6, which simply multiplies the increment of shear strength in eqn. (2), is generally suggested to be on the side of safety.

Moreover, Wu and Waldron's approach assumes that a homogenisation of the roots-soil interaction is possible at the field scale. This can be unrealistic if

the distribution of the vegetation on the slope is uneven. Finally, it should be emphasized the conceptual error inherent in applying such an approach to the stability analysis of thick non-deeply-rooted blankets subjected to possible instability phenomena.

2.2. Experimental investigation of the mechanical behaviour of rooted soil

Previous attempts to investigate the soil-root interaction by means of laboratory tests showed that the presence of roots enhances the mechanical properties of the soil-root mixture. Let us focus our attention on the case of cohesionless soil. Indeed, as long as the size of the roots is comparable to that of soil grains (*i.e.* $O(d_r) \sim O(d_s)$, where d_r and d_s denote the average diameter of roots and of soil grains, respectively), it is reasonable to assume that the interaction between roots and soil occurs through a frictional mechanism at the grain-root interface (the possible contribution of adhesion associated with the substances exuded by roots is not presently distinguished by the purely mechanical friction).

In the case of a single root filament immersed in the granular matrix and subject to the axial strain ε_r, it is reasonable to say that the larger is the strain of the rooted soil, the stronger is the response of root filaments until one of the two conditions occurs: (i) the yield stress of roots, σ_0, is reached somewhere along the root, $\sigma_r = \sigma_0$, or (ii) the condition $\sigma_r \geq (4\tau_s^{(cr)} \cdot l_s / d_s)$ occurs (*e.g.* in the middle of the filament) at the soil-root interface and the filament slips through the matrix (typically at the extremities) until the equality is recovered, where σ_r and l_s denote the tensile stress and the length of the root filament, respectively, and $\tau_s^{(cr)} = \sigma_s'^{(cr)} \tan \varphi_{sr}$ indicates the limit Coulomb friction that satisfies the equilibrium, φ_{sr} and $\sigma_s'^{(cr)}$ denoting the soil-root friction angle and the limit value of the effective stress on the roots.

This simple picture shows that, for a given configuration of the tensile stress σ_r (or equally of the strain ε_r), the mechanical behaviour of the rooted soil changes as σ'_s drops below the critical value $\sigma_s'^{(cr)}$ since the dependence of σ'_s on the value of σ_r arises. This situation, that easily occurs over the surficial layers of hill slopes, where the values of σ'_s are presumably small, is misrepresented by root-cohesion models. With the final aim to obtain a constitutive law for the homogenised rooted-soil material, it is necessary, at the present stage, to provide the tools necessary to estimate the parameters of the root-soil interaction model at the individual-filament scale. In the case that $\sigma_r < \sigma_0$ and the equality of condition (ii) is reached, the root filament slips and the friction angle at the soil-root interface, φ_{sr}, can be estimated on the basis of the equation:

$$4\sigma_s' \tan \varphi_{sr} \frac{\ell_s}{d_s} = \sigma_r(\varepsilon_r^{(cr)}) \qquad (3)$$

where $\varepsilon_r^{(cr)}$ denotes the limit axial strain of the root filaments before roots start to slip and the function $\sigma_r(\varepsilon_r)$ is the axial stress of a root filament expressed as a function of its axial strain. Indeed, this formulation is analogous to that hypothesized by MICHALOWSKI and ZHAO, [1996] for a fiber-reinforced sand.

While the geometrical characteristics and the mechanical properties of root filaments, l_s, d_s and σ_0 can be estimated by means of laboratory tests, making reliable measurements of φ_{sr} and $\sigma_r(\varepsilon_r)$ is more difficult and values can show a wide scattering because of issues associated with using natural roots (uncertainties, reproducibility, non-homogeneity of live material, effects related to biological processes). Hence, passing from the infinitesimal element to the volume element of rooted soil is crucial to investigate the mechanical response of the rooted soil to shear strain, since local effects occurring at the filament scale are filtered out by the statistical average.

The experimental methodologies most often adopted to investigate the mechanical response of rooted soil are of two types: pull-out tests, namely the instrumented uprooting of plants directly in their natural site or in the laboratory, and Direct Shear (DS) tests.

Besides technical difficulties of performing pull-out tests (*e.g.* it is not easy to preserve the integrity both of the plant and of the soil counterbalancing the pull-out force), it is not clear how the root-soil slip friction can be directly associated with the pull-out force because the shear stress τ_s results from a force that is provided from the trunk towards the extremities of the roots, which is the opposite of what actually occurs within the shear band. Moreover, to what extent roots can uniformly mobilize their tensile strength is unknown.

Indeed, DS tests override the problem of determining the position of the shear plane with respect to the roots, but the height of the DS box should be large enough to allow roots to be well contained inside the sample and develop the tensile stress. Therefore, the standard apparatus used by GRAY and OHASHI, [1983] to test fiber-reinforced soil specimens would not suffice for rooted-soil samples. To this purpose, CAZZUFFI and CRIPPA, [2005] and later MICKOVSKI *et al.*, [2009] developed an ad hoc facility to carry out DS tests on samples of soil rooted by willows. The diameter of the cylindrical samples used by MICKOVSKI *et al.*, [2009] was 15 cm while the height was varied between 10 cm and 40 cm. Indeed, MICKOVSKI *et al.*, [2009] obtained reliable estimates of the failure envelope of the rooted soil and were able to verify the effectiveness of Wu and Waldron's model for the case of willow roots. However, the question "how roots and soil are coupled during the shear strain (*i.e.* how σ_r is actually mobilized and

Tab. I – Geotechnical and soil bio-engineering countermeasures classified by prevalent action type [BOVOLENTA and PASSALACQUA, 2014].

Tab. I – Interventi di ingegneria geotecnica e naturalistica, classificati in funzione dell'azione prevalente [BOVOLENTA e PASSALACQUA, 2014].

Type	countermeasures	
	geotechnical engineering	**soil bio-engineering**
GEOMETRY MODIFICATION	• FLATTENING • UNLOADING • BUTTRESSING • SOIL/ROCK BLOCKS REMOVAL	• SLOPE SHAPING AND PREPARATION FOR PLANT GROWTH
PROTECTION	• PROTECTIVE CLIFFS OR WALLS • SHOTCRETE • EROSION CONTROL BY GEOSYNTHETICS • NETS, MESHES, BARRIERS • INFILTRATION CONTROL	• VEGETATED STONE WALLS • REVEGETATION • BIO-MATS OR BIO-NETWORKS. • FASCINES • WATTLE FENCES • SURFACE WATER CONTROL (PREFERABLY WOODEN DRAIN HALF PIPES)
SOIL AND ROCK IMPROVEMENT	• SURFACE AND SUBSURFACE DRAINAGE (TRENCHES, PIPES, WELLS, TUNNELS) • IMPROVEMENT TECHNIQUES (INJECTIONS, GROUTING, GEOSYNTHETICS) • NAILING, MICROPILES	• SEEDING • SLOPE PLANTINGS • BRUSH LAYERS • BREAST WALLS WITH SLOPE FACE PLANTINGS
STABILIZING FORCES	• RETAINING WALLS (GRAVITY, TIEBACK) • REINFORCED EARTH • ANCHORING, BOLTING • RETICULATED MICROPILES • PILES, SHAFTS	• VEGETATED STONE WALLS • LIVE WOODEN CRIBWALLS • VEGETATED GABIONS

transferred to the granular matrix) thereby improving the ductility of the mixture" is left without a clear response by DS tests.

Presently, tensile tests on individual roots were preliminarly made in order to be able to identify the contribution of roots in the mechanical behaviour of the rooted soil. In fact, the results of tensile tests, which are briefly described in the following, help us to determine the function $\sigma_r(\varepsilon_r)$ in the equation 3. Thereafter, the mechanical response of saturated rooted-soil samples to an increasing deviatoric stress was investigated by means of triaxial tests in principle similar to those performed by MICHALOWSKI and ZHAO [1996] to study the reinforcement effect of fibers dispersed in a sandy soil. In particular, both the plants and the soil were sampled from the Liguria region which are fairly representative of the Mediterranean environment. Then, the main results of the triaxial tests are discussed.

2.2.1. TENSILE TESTS ON INDIVIDUAL ROOTS

The strength of individual root filaments to cyclic progressively-increasing elongation was tested by means of tensile tests. High precision measurements of the tensile strength were made by a Zwick/Roell testing machine at the Material Laboratory of the Department of Civil, Chemical and Environmental Engineering of the University of Genoa. The pictures in figure 2 show the experimental facility during one of the tensile tests presently described.

Three species of plants were considered, *Spartium-Junceum*, *Ligustrum* and *Arbutus-Unedo*, which are frequently used in soil bio-engineering works in Liguria (Italy). While *Spartium-Junceum* develops taproots, namely a primary root filament from which secondary roots depart, the roots of *Ligustrum* and *Arbutus-Unedo* are branched (*i.e.* several primary roots are present). The values of the average diameter of root filaments used in the tensile tests are reported in table II. Figure 3a shows the stress-strain curves of the root filaments obtained with the tensile tests. The strain ε_r was increased at a constant rate, then decreased and increased again, in order to observe the response of the filaments to unload-reload cycles. Finally, roots were led to the breaking point with constant strain rate. During the unload phases the material showed a linear elastic behaviour with a slight hysteresis during the re-loading. In particular, the three curves highlighted in figure 3a show a change of slope when the strain reaches approximately 3%, which follows the break of the cortical shell of roots which is stiffer than the inner cylinder. This evidence was observed by means of microscopy movies made during the tensile tests (*e.g.* see Fig. 3b

Tab. II – Values of the parameters $\hat{E}$ and ξ and of the average diameter $\langle d_r \rangle$ of root filaments estimated on the basis the tensile tests.
Tab. II – Valori dei parametri $\hat{E}$ and ξ e del diametro medio $\langle d_r \rangle$ dei filamenti radicali, stimati in base alle prove di trazione.

species	$\langle d_r \rangle$ [mm]	$\hat{E}$ [MPa]	ξ [-]
Spartium-Junceum	0.57	340	0.10
Ligustrum	0.75	240	0.18
reconstituted	0.60	270	0.02

showing a *Ligustrum* filament at the instant marked in figure 3a with a star). On the other hand, the inner cylinder is more ductile and can provide a significant tensile strength up to very large deformation stages (see the picture of figure 2c which was taken after a tensile test on a *Ligustrum* root filament). Young's modulus of the root filaments, E, was calculated as a function of ε_r (the diagrams are shown in figure 1b of MAZZUOLI *et al.*, 2016).

Indeed, it was found that E was nearly constant as long as ε_r was smaller than 3% while non-linear-elastic plastic deformation of root filaments was observed for larger values of strain. For small strains (ε_r<1%), the value of E is not constant and the mechanical behaviour is similar to that described for large strains.

MAZZUOLI *et al.*, [2016] showed that for ε_r<1% the value of the tensile stress σ_r associated with the strain ε_r could be approximated by the following expression:

$$\sigma_r = \frac{\hat{E}}{100}\,\varepsilon_r^{\xi} \qquad (4)$$

where $\hat{E}$ denotes the average value of E for 1% < ε_r <3%. The values of $\hat{E}$ and ξ computed for the present cases are shown in table II.

It is worthwhile to point out that for a wide range of strain that can be reasonably attained in a slope (1% < ε_r<10%) the value of E ranges between O(100) [MPa], *e.g.* like a rubber, and O(500) [MPa]. The highest values of E, which are reached for strains smaller than 0.1%, are associated with the cortical shell and, in fact, are comparable with Young's modulus of wood.

Therefore, although the dependence of the tensile stress on the elongation of filaments is weak for small or very large deformations (plastic-like deformation), it appears significant for values of the strain which are relevant for soil bio-engineering purposes, whence it should be taken into consideration by a constitutive model for the rooted soil.

The interested reader can find further details of the tensile tests in MAZZUOLI *et al.*, [2016].

Let us remark that the diameter of root filaments presently considered was smaller than 1 mm, which is approximately the size of sand grains (see section

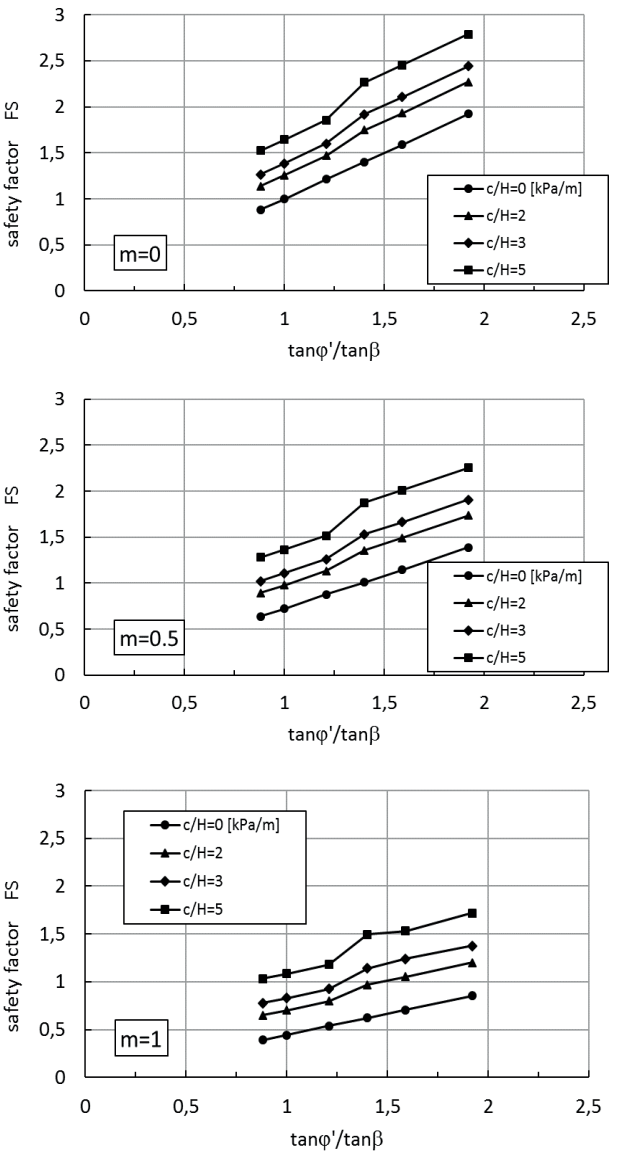


Fig. 1 – Safety factor as a function of tanφ'/tanβ for typical values of the parameters m and c/H.
Fig. 1 – Fattore di sicurezza in funzione del rapporto tanφ'/tanβ per valori tipici dei parametri m e c/H.

2.2), while the mechanical response of larger filaments can be qualitatively and quantitatively different, as shown, among others, by DE BAETS *et al.*[2008] and by CAZZUFFI *et al.* [2014]. Indeed, larger roots typically manifest fragile behaviour and reach smaller values of tensile stress at the failure than thin root filaments.

2.2.2. TRIAXIAL TESTS ON ROOTED SAMPLES

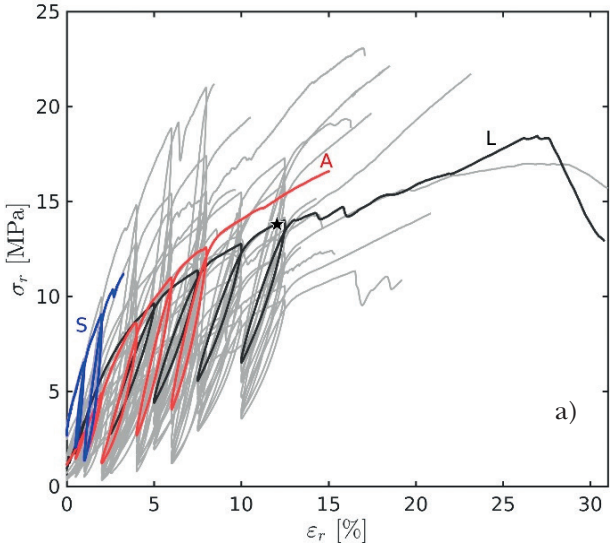
Previous attempts to investigate the mechanical response of sand reinforced with threads to triaxial compression showed that the strength of the reinforced material was increased by the presence of filaments, which manifested itself in an apparent in-

a) b) c)

Fig. 2 – *a*) Experimental facility used for the tensile tests. *b*) Detail of anchoring of a root filament to the Zwick/Roell tensile-test machine. *c*) Enlargement of a root of *Ligustrum* after its failure during a the tensile test: cortical and internal cylinder can be clearly distinguished.

Fig. 2 – a) Apparecchiatura sperimentale usata per le prove di trazione. b) Dettaglio dell'ancoraggio di un filamento di radice alla macchina di trazione Zwick/Roell. c) Ingrandimento di una radice di Ligustrum successivamente alla rottura avvenuta durante una prova di trazione: si osservano chiaramente distinti il cilindro corticale e quello interno.

crease of stiffness of the composite material at stresses that would have caused the failure of an equivalent unreinforced sample [Di Prisco and Nova, 1993]. The use of natural fibers or filaments introduces uncertainties associated with their mechanical properties that synthetic threads have not. Indeed, geometrical (*e.g.* twisting, architecture), biological (*e.g.* adhesion, anchoring) and material characteristics of natural roots are heterogeneous and often difficult to be estimated. These features are misrepresented by experiments carried out on synthetic threads. Also the specimens reconstituted by Gray and Ohashi, [1983] or by Zhang *et al.* [2010] with in-



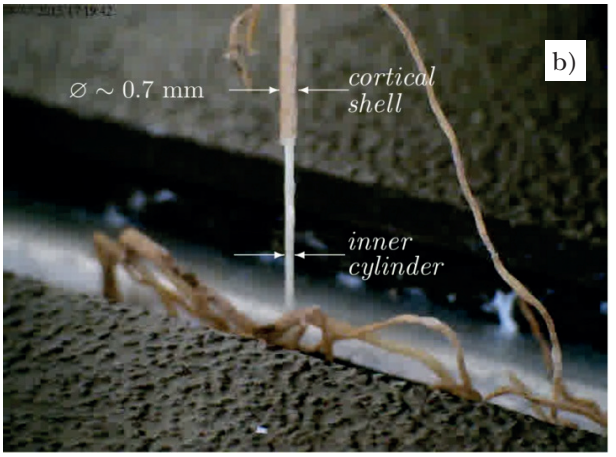


Fig. 3 – Tensile tests carried out on roots from three different plant species. *a*) Tensile stress as a function of the axial strain. In particular three tests are highlighted by black (L, *Ligustrum*), blue (S, *Spartium-Junceum*) and red (A *Arbutus-Unedo*) lines. *b*) A frame of the microscopy movie at the instant indicated by the star in panel (*a*): the cortical shell appears well detached from the inner cylinder.

Fig. 3 – Prove di trazione effettuate su tre diverse specie di piante. a) Tensione di trazione (assiale) in funzione della deformazione assiale. Con linea nera (L, Ligustrum), blu (S, Spartium-Junceum) e rossa (A Arbutus-Unedo) sono evidenziate in particolare tre prove. b) Fotogramma di un video registrato al microscopio relativo all'istante indicato da una stella nera nel pannello (a): l'involucro corticale appare ormai separato dal cilindro interno.

Fig. 4 – Moulds before the preparation of the samples used for the triaxial tests. Membranes were preliminarily mounted and drainages were made at the bottom in order to allow plants to grow inside.

Fig. 4 – Supporti dei campioni prima della preparazione dei provini usati per le prove triassiali. Le membrane sono sistemate preliminarmente, mentre, per permettere alle piante di crescere nei provini, sono praticati sul fondo dei fori di drenaggio dell'acqua.

clusions of natural fibers cannot be considered fully representative of naturally rooted soil because plants need to grow into the soil to develop their natural anchoring. Actually, ZHANG *et al.* [2010] performed triaxial compression tests on soil samples of standard size (80mm × Ø39.1 mm) which could contain only single or pairs of cuts of root filaments.

Therefore, special cylindrical moulds were designed which allowed plants naturally to develop their own roots inside (see Fig. 4). The size of the moulds (140mm × Ø70 mm) was suitable for relatively large triaxial cells. The tests were performed at the Geotechnical Laboratory of Turin Polytechnic.

Soil samples were picked up from hill fields in Liguria, which consisted in clayey sand (SC of the USCS classification). The fine and gravel portions were preliminarily sifted out. The removal of the fine part allows the resistance at the root-soil interface to be predominantly frictional. After the preliminary sieving, sorted uniformly-graded sand was obtained (SW of the USCS classification). Indeed, the grain distribution of the material (which was reported in figure 1a of MAZZUOLI *et al.*, 2016) was characterized by uniformity and gradation coefficients equal to 6.67 and 1.23 respectively, and by D_{60}=1 mm. Both wet and dry sieving procedures were carried out. A weak particle cohesion was expected in the specimens where only the dry procedure was employed. In fact, the fine material contained organic matter which cemented in small agglomerates that could be destroyed and removed only by wet sieving. The three plant species indicated in the previous section were used to prepare the specimens for the triaxial tests.

Tab. III – Values of the unit weight in dry condition and of the reduced void ratio for the samples used for the triaxial tests.

Tab. III – Valori del peso dell'unità di volume secco e dell'indice dei vuoti ridotto dei campioni sottoposti a prove triassiali.

# sample	species	p'_c[kPa]	γ_d[kN/m^3]	$e_{red}^{(in)}$
S1	*Spartium-Junceum*	40	11.8	1.09
S2	"	75	10.9	1.21
S3	"	300	12.2	1.03
L1	*Ligustrum*	40	9.81	1.35
L2	"	75	10.4	1.28
L3	"	300	10.4	1.17
R1	reconstituted	40	12.0	1.20
R2	"	75	12.3	1.15
R3	"	300	12.1	1.18

Tab. IV – Friction angle and cohesion obtained from the failure envelope obtained in standard triaxial tests.

Tab. IV – Angolo di resistenza al taglio e coesione efficace ottenuti dale prove triassiali convenzionali.

species	φ'[deg]	c'[kPa]
Spartium-Junceum	32.0	7.5
Ligustrum	38.1	5.0
reconstituted	33.9	5.2

Presently, the results obtained for the samples rooted by *Ligustrum* and *Spartium- Junceum* are showed and discussed with the aim of identifying the mechanisms of action of roots in a hill-slope that are currently not captured by models (*e.g.* root-cohesion models). In particular, our attention focuses on the processes occurring during a heavy rainfall which saturates the soil. Two issues arise: (i) quantifying the root reinforcement when rooted soil is already saturated (triaxial tests in undrained conditions), and (ii) describe the deformation process that rooted soil experiences during the saturation process. The first question was addressed by carrying out standard CIU triaxial tests on saturated samples, preliminarily consolidated at different pressures, while for the second one an ad hoc stress/saturation path was used which mimicked the condition of a hill slope at the first stages of a rainfall. Moreover, the same tests were then repeated on unreinforced samples for the purpose of comparison. It is worthwhile to point out that the triaxial tests were stopped for technical reasons when the axial strain reached about 20%.

Table III shows the values of the dry unit weight and of the initial void ratio of the samples used for the triaxial tests presently considered while the friction angle φ' and the cohesion c' obtained from the failure envelope of the peak shear strength observed in the triaxial tests are indicated in table IV. The values of the initial void ratio were suitably reduced in order to take into account the presence of the roots.

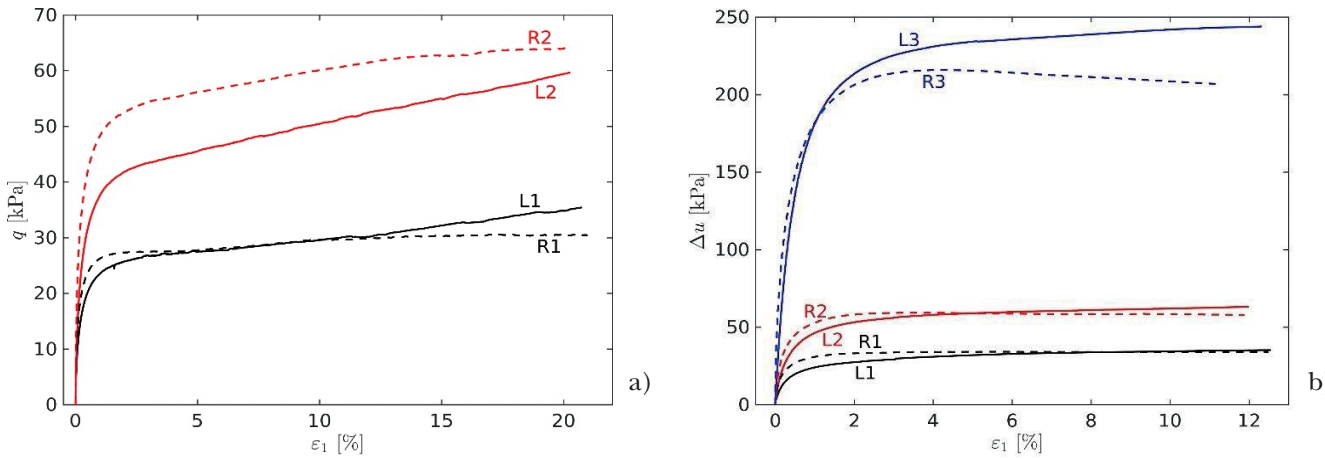


Fig. 5 – *a)* $q - \varepsilon_1$ diagrams for triaxial tests on rooted ("L" label, solid line) and non-rooted ("R" label, broken line) samples. Red lines: p'_c = 75 kPa; black lines: p'_c = 40 kPa. *b)* $\varepsilon_1 - \Delta u$ diagrams for the reconstituted samples ("R" label) and samples rooted by *Ligustrum* ("L" label). Black lines: sample R1, L1; red lines: samples R2, L2; blue lines: samples R3, L3 (see Tab. III). *Fig. 5 – a) Diagrammi* q – ε1 *relativi alle prove triassiali su campioni di terreno radicato ("L", linea continua) e non radicato ("R", linea tratteggiata). Linee rosse:* p'c *= 75 kPa; linee nere:* p'c *= 40 kPa. b) Diagrammi* ε1 – Δu *per i campioni ricostituiti ("R") e i campioni radicati da* Ligustrum *("L"). Linee nere: campioni R1, L1; linee rosse: campioni R2, L2; linee blu: campioni R3, L3 (cfr. Tab. III).*

In particular, the reduced void ratio was defined as $e_{red}^{(in)} = (V^{(in)} - V_r)\, G_s / W_s^{(in)} - 1$, where $V^{(in)}$ and V_r denote the initial volume of the sample and the volume of the roots contained in the sample, G_s=2.7 is the specific gravity of soil grains and $W_s^{(in)}$ indicates the initial weight of the granular matrix. Fluctuations of the values of the dry unit weight, γ_d, and $e_{red}^{(in)}$ are due to the uncertainties introduced during the phase of preparation of the samples. However, for the purpose of the present contribution, these fluctuations are reasonably small.

MAZZUOLI *et al.*, [2016] discussed the results of CIU triaxial tests carried out on samples rooted by *Ligustrum*. They observed a significant increase of the friction angle, while the cohesion of the composite material did not remarkably change with respect to the non-rooted case. The enhancement of the frictional properties of the rooted soil can be associated with processes occurring during the final phase of deformation when the material tends to dilate laterally (although volume was constant). Indeed, in the absence of roots, the material reaches a plateau strength at large deformation. A similar behaviour was not exhibited by rooted samples. In fact, also at large deformation levels the rooted material continued to mobilize resistance which increased with the strain at a constant rate, while the non-rooted material, that was initially stiffer, rapidly attained a limit value (see Fig. 5a). The action of root filaments on the granular matrix results in the excess of pore water pressure, Δu, as shown in figure 5b. The increase of Δu in the rooted sample is probably caused by the confinement action of roots which counteract the lateral strain of the sample, thereby impeding the reduction of the excess pore pressure. Indeed, this effect was not observed by the measurements on the non-rooted sample. A consequence of the increase of pore pressure is the decrease of mean stress p' without a contextual decrease of deviatoric stress q. The effect of roots is markedly weaker in the samples rooted by *Spartium-Junceum* because root filaments were sparser and distributed in non-homogeneous fashion (diagrams are presently omitted).

Finally, the stress conditions occurring along slopes subject to an intense storm were mimicked by means of a triaxial stress path that is here denoted as "failure induced by saturation" (FIS). Presently, the results of two of these tests are shown, which were performed on a non-rooted specimen and on a sample rooted by *Ligustrum*. In particular, figure 6 shows the trend of q as a function of the axial strain for these triaxial FIS tests. The samples were initially loaded (first phase), in drained conditions and with a constant strain rate, up to $2/3 q_f$, q_f denoting the failure deviatoric stress obtained with the previous L-series of tests. Then, samples were saturated (second phase), keeping the values of p' and q constant, while their strain was measured and, finally, were brought to failure in undrained conditions (third phase). The mechanism of action of roots described above is clearly shown also by the results of triaxial FIS tests. In particular, figure 6 shows that the sample without roots experiences a larger strain during the saturation phase than the rooted sample and a softening behaviour during the following undrained shearing phase whereas the rooted sample hardens before failing reaching a peak of q that was larger of nearly 50%.

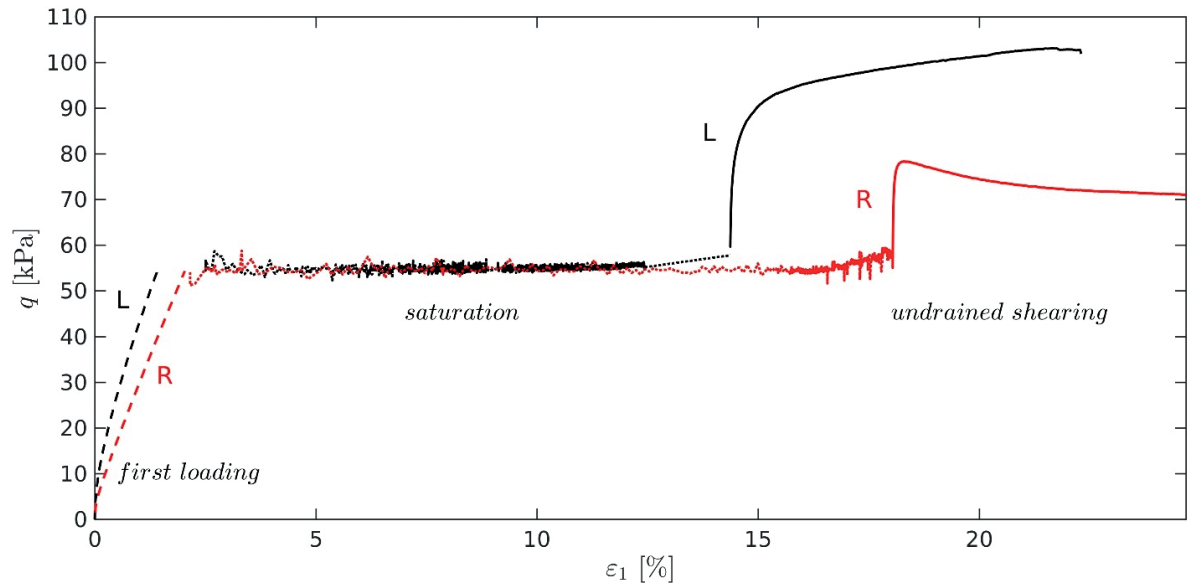


Fig. 6 – ($q - \varepsilon_1$) curves for triaxial FIS tests on rooted (black line labeled by "L") and non-rooted (red line labeled by "R") samples. Different line styles are used to indicate the three phases of triaxial FIS tests.
Fig. 6 – Curve ($q - \varepsilon_1$) *per le prove triassiali FIS effettuate su campioni di suolo radicato ("L", linea nera) e non radicato ("R", linea rossa). Sono stati utilizzati stili di linea differenti per distinguere le tre fasi che caratterizzano le prove FIS.*

It is worthwhile to note that the initial conditions of the rooted and reconstituted non-rooted samples approximately coincided (both in terms of void ratio and specific weight) and their mechanical response during the first phase was also very similar. However, during the following phase of saturation, the differences between the mechanical responses of the two materials were more evident.

This is also related to the fact that the deviatoric stress $2/3q_f$ reached at the end of the first loading phase is larger than 2/3 of the failure deviatoric stress associated with the non-rooted sample. Consistently, the non-rooted sample shows larger strains during the saturation phase. Therefore, the surficial layer of vegetated hill slope would have larger residual resistance after a rainfall than in absence of vegetation, the additional resistance of roots being available also for deviatoric stresses relatively far from the failure.

The development of the excess pore pressure as a function of p' and q during the third phase of FIS tests *(i.e.* undrained compression) is shown in figure 7. The non-rooted sample attained a peak of q at a value approximately equal to q_{cv}, then failed and mobilized smaller residual deviatoric stress while continued to "dilate". Indeed, this behaviour is typical of loose sand. However, the rooted sample did not reach the failure although the axial strain reached 20%. Instead, while p' increased, the contextual increase of the excess pore pressure was prevented by the action of roots and the values of q at large strains remained limited. Thus the action of roots apparently consists in providing the material with a confinement action which prevents the deformation of the sample. This mechanical behaviour is commonly observed in CIU triaxial tests on densely packed sand (although presently the void ratio was almost the same as that of the reconstituted - non-rooted - specimen).

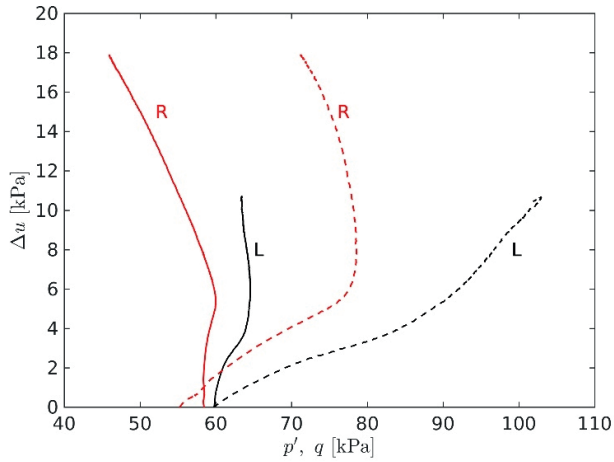


Fig. 7 – Excess pore water pressure plotted as a function of p' (solid lines) and of q (broken lines) for the FIS tests carried out on the reconstituted sample ("R", red lines) and on the sample rooted by *Ligustrum* ("L", black lines).
Fig. 7 – Sovrappressione interstiziale in funzione di p' *(linee continue) e di* q *(linee tratteggiate) per le prove FIS effettuate su campioni di terreno ricostituito ("R", linee rosse) e su campioni di terreno radicato da* Ligustrum *(L, linee nere).*

Fig. 8 – Live wooden cribwall.
Fig. 8 – Esempio di palificata viva.

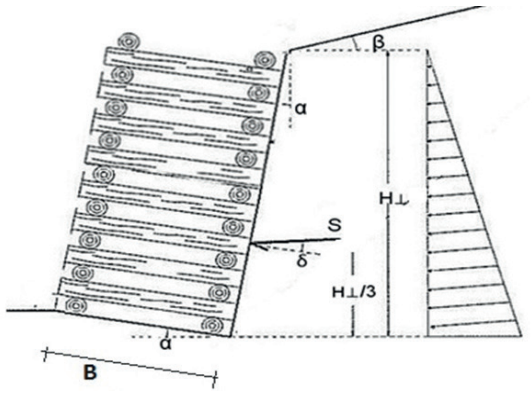


Fig. 9 – Schematic cross section of a LWC.
Fig. 9 – Schematica sezione trasversale di un palificata viva a parete doppia

This is, to the knowledge of the authors, the first time that the action of roots, naturally grown inside specimens of a cohesionless soil, was clearly described on the basis of triaxial test results and quantified under realistic stress conditions.

3. Live wooden cribwalls

Live Wooden Cribwalls (LWCs) can be placed along slopes and embankments or at their base and consist in superimposed layers of logs arranged with the purpose of forming a sort of cage for inert material and live plants (see Fig. 8). In LWCs, the advantages of an immediate stabilizing effect and of the progressive improvement of their performance associated with the growth of vegetation combine effectively. Indeed, this technique can be considered one of the most efficient soil bio-engineering countermeasures to retain cuts of moderate high.

LWCs are arranged in single or double cribwalls, which are the assembly of wooden logs and anchor logs (deprived of their bark) held together with nails or bolts. The longitudinal beams are alternated to the transverse beams in order to realize an open structure. The laying surface of the structure should have an inclination ranging from 5° to 10° with respect to the slope [FLORINETH and GERSTGRASER, 1996]. The space between the logs is filled with soil and plants, which should not stick out the wall more than a quarter of their length.

Additional reinforcement is progressively attained by LWCs as the live cuttings or branches planted into the structure, similarly to brush layering, grow. This contribution can be maximised by a regular maintenance and control of the aboveground part of plants that should be kept short. The proper selection of plant species and the correct planting of cuttings are also fundamental issues. It is convenient to use green willow branches and strong rooted pioneer plants which grow relatively fast. In order to let plants be well exposed to the sun light, the wall face should be inclined.

Some of the advantages of LWCs, which can make them an attractive alternative to traditional cribwalls or massive walls are the weight, the capability to sustain relatively large displacements, the pleasant appearance (especially in natural contexts) and the ease of construction. Moreover, such structures are able to provide a good drainage. However, their size (typically low and squat) and the dependence on the time required by the cuttings to grow can limit their use.

In Italy, manuals are periodically prepared and updated by AIPIN (*Associazione Italiana per l'Ingegneria Naturalistica*) or by regional authorities. These manuals cannot not be considered as a substitute of the technical regulations but as a tool to help practitioners in designing LWCs. Indeed, in Italy, LWCs are presently regulated by the current regulations *(i.e.* Norme Tecniche per le Costruzioni (NTC) and related integrations) and should undergo the analyses required for "mixed retaining walls".

The correct assessment of actions and resistances as well as the fulfilment of imposed safety levels, often marginally considered are key issues especially if LWCs are relatively high and when multiple LWCs are installed in step-like arrangement along the slope.

Mistakes at the sizing stage can compromise the stability of the work and are often due to the wrong use of empirical rules. Indeed, the possibility to meet with construction errors is higher than in traditional engineering works and the following mistakes can be frequently observed:

- the not proper linking of logs, causing breakage and emptying of LWCs;
- the improper disposal of the logs to the plan of foundation. Starting the construction with the anchor logs, the structure may be rapidly subject to sliding;

Tab. V – Values of parameters adopted in the parametric analysis.
Tab. V –Valori delle grandezze adottate nelle analisi numeriche parametriche.

Width	B	2	[m]
Length	L	12	[m]
Wooden log diameter	D	0,2	[m]
Wooden log length	L_c	4	[m]
Wooden anchor log length	L_t	2	[m]
In situ soil: Dry soil unit weight	γ_d	18	[kN/m^3]
In situ soil: Saturated soil unit weight	γ	21	[kN/m^3]
In situ soil: Soil effective unit weight	γ'	11	[kN/m^3]
Soil filling: Dry soil unit weight	$\gamma_{b,d}$	17	[kN/m^3]
Soil filling: Saturated soil unit weight	γ_b	19	[kN/m^3]

- the absence of alternation of the logs and anchor logs, which may lead to local breakages;
- the use of plants with length not sufficient to reach the ground overleaf: in this case the stabilizing effect provided by roots fails;
- the total absence of live plants;
- the construction of the wooden casing before filling and positioning the plants, which could affect the stability of the cribwalls and the growth of plants;
- the wrong estimate of the dimensions of individual cribwalls *(i.e.* ratio width/height *B/H*).

In the following, the importance of the preliminary design of LWCs is emphasized, taking also into account aspects related to the influence of vegetation growth and the degradation of physical and mechanical properties of these particular "alive structures". The construction procedures of cribwalls are not presently described.

3.1. Preliminary sizing of LWCs

A parametric analysis has been carried out to verify the validity of empirical rules that are often adopted for the sizing of LWCs. The response of LWCs is evaluated for different geometrical configurations, geotechnical parameters *(i.e.* the angle of inclination the foundation plane α, the slope angle β and the soil friction angle φ') as well as the groundwater conditions, assuming the values of the parameters indicated in table V.

A sketch of LWC is shown in figure 9 where symbols that will be used hereafter are also indicated. The stability conditions of the structure are verified according to the current Italian regulations, focusing on sliding, overturning and bearing capacity. The global stability is analysed in section 3.3 where the possibility to assembly multiple LWCs in a sequence along the slope is also discussed.

Both saturated and dry soil conditions have been considered, which are limit cases. However, for a preliminary sizing of the values of the ratio of the breadth, *B*, to the height, *H*, of LWCs water pressure is applied over the entire back side of the wall, which is on the side of safety.

The values of *B/H* fulfilling stability according to the NTC are reported in table VI for some values of α, β and φ'. In particular, our attention focused on sliding and bearing capacity limit states. For instance, [SIMONATO and BISCHETTI, 2003], who performed a parametric analysis of LWC stability, did not consider the bearing capacity and obtained values of *B/H* slightly smaller than those indicated in table IV.

It is clear that values of the ratio *B/H* smaller than 1 (*e.g. B/H = 0.5* is often adopted to size LWCs on the basis of empirical rules) do not guarantee the fulfilment of the stability analyses with the exception of soils with good mechanical properties in dry conditions (*i.e.* high values of the friction angle φ') and/or for small slope inclination. Instead, a reasonable first estimate of $B/H \cong 1$ is, as indicated by [VALENTINI, 1912].

The designer, certainly, must verify that the geometry of LWCs assumed in the preliminary phase, satisfies the ultimate and serviceability limit state analyses, also considering the specific (hydraulic, morphological, geotechnical, loading, etc.) conditions of the site.

Finally, it is not advisable to use LWCs higher than approximately 4 meters. In case it is necessary to support higher cuts or to stabilize a wide area, the assembly of multiple LWCs placed in step-like arrangement along the slope (see Fig. 10) is advisable. The possibility for adjacent "steps" to interact should be also considered in the stability analysis (see section 3.3).

3.2. Evolutionary analysis of LWCs

In order to emphasize the importance of the live material, which plays a significant role in bio-engineering works, the time-evolution of the LWC performance, contextual to the growth of vegetation, is presently briefly analysed. The aim of the analysis is to understand how much the stability of LWCs is affected by the development of the roots of the plants installed into the cribwall face.

The studies of SCHIECHTL [1991] and of PRETI and CANTINI [2002] concerning the growth of cuttings of *Salix Purpurea* (commonly termed purple willow) in a debris site in North Tirol at an altitude of 700 m above mean sea level are taken as a reference. *Salix Purpurea* is often used in soil bio-engineering for its excellent bio-technical characteristics, the maximum tensile stress supported by the roots of this species being approximately equal to 36 MPa. Figure 11 shows the increase of height, width and volume of the aboveground part of the *Salix Purpurea*

Fig.10 – LWCs placed in step-like arrangement along a slope.
Fig. 10 – Serie di palificate vive a parete doppia lungo un pendio.

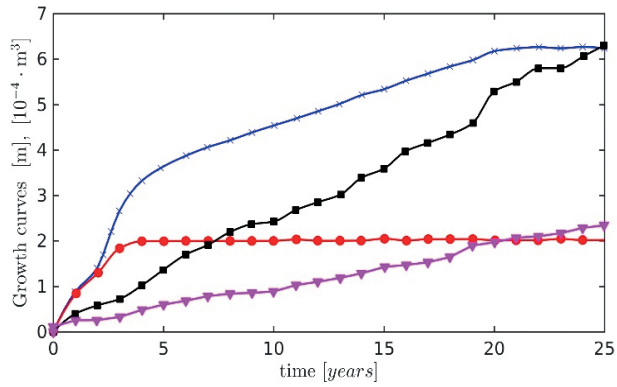


Fig. 11 – Growth curves of Salix Purpurea (from Schiechtl, [1991]). Blue (crosses): height of the aboveground part [m], red (dots): root depth [m], black (squares): width of the aboveground part [m], magenta (triangles): volume of the aboveground part [10^{-4} · m^3].
Fig. 11 – Curve di accrescimento di Salix Purpurea (da Schiechtl, [1991]). Blu (croci): altezza della parte fuori terra [m], rosso (punti): profondità delle radici [m], nero (quadrati): larghezza della parte fuori terra [m], magenta (triangoli): volume della parte fuori terra [10^{-4} · m^3].

as well as its rooting depth during a period of twenty-five years.

A parametric analysis, similar to that discussed in section 3.1, was performed considering the plant growth. The following values of the parameters were chosen: α=10°, β=10°, φ'=34°, B/H = 1 and B/H = 2 m.

Since trunks (logs) have a diameter of about 0.2 m, the cuttings can be planted in each of the five inter-spaces between the logs of the cribwall front. It can be assumed to insert five cuttings/meter. The increase in shear strength provided by the roots was estimated by using Wu and Waldron's model (see section 3.1) throughout a period of 24 years. The contribution of plant roots was taken into account in the LWC safety analyses (Fig. 12).

The strength contribution offered by the roots was reduced by 75% in order to consider possible uncertainties. In fact, as mentioned above, a number of studies have shown that Wu and Waldron's model often leads to an overestimation of the increase in shear strength offered by the roots. Nonetheless, figure 12 shows that the development of the roots can significantly improve the stability, and the trends of the safety factors are non-negligibly increased, especially with regard to overturning and sliding.

It is worthwhile to remark that the presence of the aerial part of the plants was not taken into account in the above analyses. Indeed, the importance of a proper maintenance lies in the growth control of the aboveground part of the plants installed into the cribwalls. Indeed, the uncontrolled growth of the aerial part of the plants inserted in the cribwall, causes the reduction of the safety factors (in particular the overturning and the bearing capacity), which are affected by the weight of the aerial part of vegetation. This, in fact, influences the increase of the overturning moment and causes the reduction of the effective width of the foundation. Therefore, pruning and crop care of cuttings should be periodically planned to guarantee the effectiveness of the intervention.

3.3. Preliminary analysis of multiple LWCs

The use of multiple LWCs is necessary when the height of the backfill soil is greater than what can be retained by a single live wooden cribwall, considering the limiting value H~4 m suggested by experience. The design of multiple LWCs requires to estimate the spacing between the cribwalls, *d*, and to assess the global safety of the re-profiled slope. Furthermore, an important issue to consider is the possible loss of serviceability (or collapse) of a single LWC and the consequent influence on the other elements placed along the slope (and on the slope itself).

This kind of analysis can be performed by means of limit equilibrium methods or with a numerical approach. The latter approach is commonly preferred because it allows us to predict the development of possible local/global failures along the slope and to simulate the damage and/or local instability of one (or more) LWCs.

A series of simple but representative FEM analyses were performed by using PLAXIS 2D software, in order to:

– analyse the global stability of the re-profiled slope;
– estimate the wall spacing *d* such that each element of the multiple LWCs can be verified sep-

Tab. VI – Minimum values of *B/H* fulfilling limit states.
Tab. VI – Valori minimi del rapporto B/H per il soddisfacimento dello stato limite ultimo.

Dry soil		ϕ'=26°				ϕ'=30°				ϕ'=34°				ϕ'=38°			
B/H		α				α				α				α			
		0°	5°	10°	15°	0°	5°	10°	15°	0°	5°	10°	15°	0°	5°	10°	15°
β	0°	0.91	0.63	0.53	0.50	0.67	0.48	0.38	0.32	0.48	0.36	0.29	0.22	0.33	0.28	0.22	0.16
	10°	1.11	0.77	0.59	0.53	0.77	0.53	0.42	0.34	0.53	0.38	0.30	0.23	0.37	0.29	0.23	0.17
Saturated soil		ϕ'=26°				ϕ'=30°				ϕ'=34°				ϕ'=38°			
B/H		α				α				α				α			
		0°	5°	10°	15°	0°	5°	10°	15°	0°	5°	10°	15°	0°	5°	10°	15°
β	0°	2.00	1.43	1.25	1.00	1.67	1.25	1.00	0.83	1.25	1.00	0.83	0.67	1.11	0.91	0.71	0.59
	10°	2.00	1.43	1.25	1.11	1.67	1.25	1.00	0.83	1.43	1.11	0.83	0.67	1.11	0.91	0.71	0.59

arately (*i.e.* the maximum value of the relative spacing *d/B* for which a LWC interacts with the others);
– provide useful indications on the influence of local damages or loss of stability (of the type described in section 3.1) on the overall performance of the stabilizing system of LWCs.

A scheme of the configuration used for the numerical simulations is sketched in figure 13. Three LWCs were placed along the hill slope (slope 1:2) which are built progressively from no. I, at the base, to no. III at the top. Each LWC is characterized by the ratio $B/H = 1$, with breadth $B = 2$ m. The values of the ratio d/B presently considered are 0, 0.5, 1 and 2.

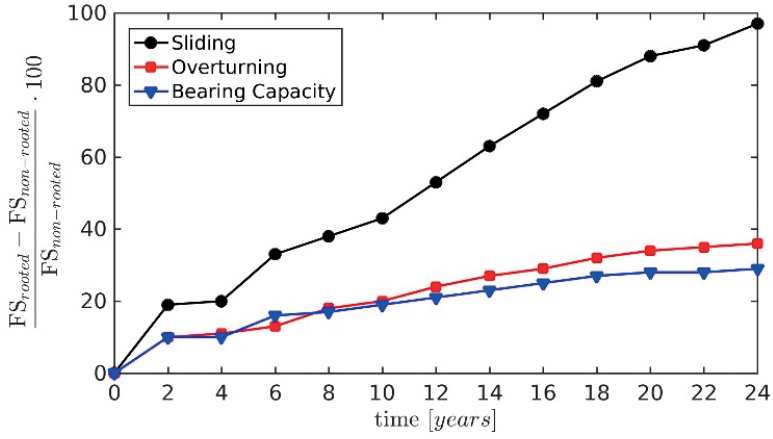


Fig. 12 – Increase of the safety factors of a LWC as a function of the growth time of the plants.
Fig. 12 – Aumento del fattore di sicurezza di una palificata viva a parete doppia in funzione del tempo di accrescimento delle piante.

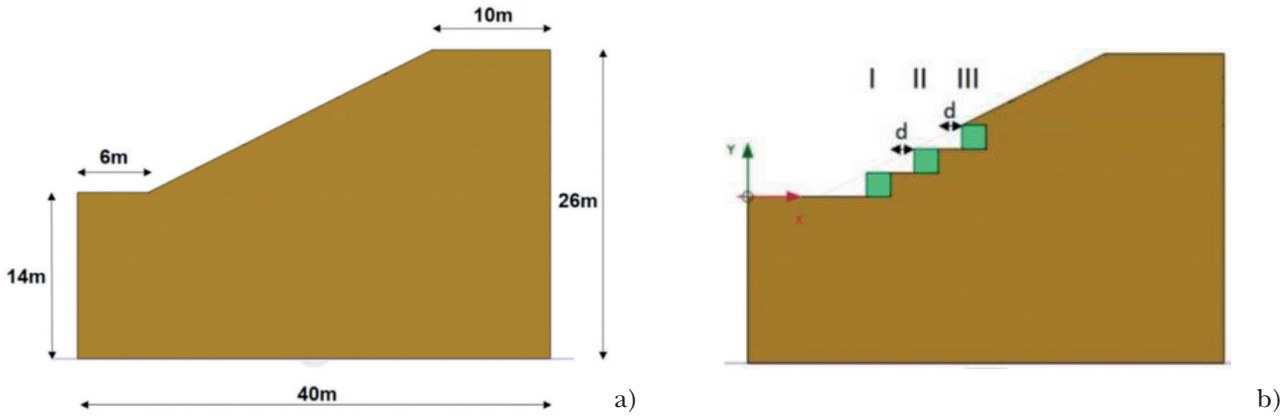


Fig. 13 – *a)* Scheme of the slope used for the numerical analyses model; *b)* Scheme of multiple LWCs.
Fig. 13 – a) Schema di pendio per le analisi numeriche; b) Schema di palificate vive (LWCs) multiple.

Tab. VII – Values of parameters kept in FEM analyses.
Tab. VII – Valori dei parametri adottati nelle analisi numeriche FEM.

Natural slope			
Natural Slope Inclination	1:2		
In situ soil			
Soil Cohesion	c'	2	[kN/m^2]
Friction angle	φ'	32	[°]
Dilatancy angle	ψ	0	[°]
Dry soil unit weight	γ_d	18	[kN/m^3]
Saturated soil unit weight	γ	21	[kN/m^3]
Young's modulus	E	35000	[kN/m^2]
Poisson's ratio	ν	0.3	
LWC			
Width	B	2	[m]
Height	H	2	[m]
Wall spacing	d	variable	[m]
Foundation plane angle	α	0	[°]
Slope angle behind the LWC	β	0	[°]
Wooden log diameter	D	0,2	[m]
Wooden anchor log length	L_t	2	[m]
LWC: Soil Cohesion	c'	50	[kN/m^2]
LWC: Friction angle	φ'	32	[°]
LWC: Dilatancy angle	ψ	0	[°]
LWC: Dry soil unit weight	γ_d	17	[kN/m^3]
LWC: Saturated soil unit weight	γ	19	[kN/m^3]
LWC: Young's modulus	E	100000	[kN/m^2]
LWC: Poisson's ratio	ν	0.3	
Damaged LWC			
Width	B	2	[m]
Height	H	2	[m]
Wall spacing	d	variable	[m]
Foundation plane angle	α	0	[°]
Slope angle behind the LWC	β	0	[°]
Wooden log diameter	D	0,2	[m]
Wooden anchor log length	L_t	2	[m]
LWC: Soil Cohesion	c'	25	[kN/m^2]
LWC: Friction angle	φ'	32	[°]
LWC: Dilatancy angle	ψ	0	[°]
LWC: Dry soil unit weight	γ_d	12	[kN/m^3]
LWC: Saturated soil unit weight	γ	14	[kN/m^3]
LWC: Young's modulus	E	45000	[kN/m^2]
LWC: Poisson's ratio	ν	0.3	

The Mohr-Coulomb failure criterion is adopted. Soil parameters are assumed constant along the slope (values in Tab. VII); neither water table nor hydraulic flows are considered.

LWCs are simulated by nearly "rigid blocks" of fictitious stiff and cohesive soil (see the values of the parameters indicated in Tab. VII) for which the possibility of internal failures is always prevented during the simulations, except in the cases where the internal physical/mechanical properties of individual blocks are reduced on purpose to realistic levels in order to simulate the damage of LWCs.

Each construction step has been simulated (Fig. 13b). A safety analysis (*φ-c reduction* procedure) was performed at the end of each construction stage, in order to assess the minimum global safety factors (FS) of the slope and to identify the zone affected by the maximum deviatoric strains.

The results of the FEM analysis are shown in table VIII and figures 14 and 15.

The values of the safety factor tend slightly to increase as d increases. In some cases, the benefit in terms of slope stability resulting from additional LWCs is overcome by the destabilising effect of the weight of the LWCs. In these cases, the relevance of building multiple LWCs is only associated with the

Tab. VIII – Safety factors by FEM analyses of multiple level LWCs: influence of inter wall distance d.
Tab. VIII – Coefficienti di sicurezza dalle analisi FEM di palificate vive multiple (LWCs): influenza della distanza d.

d	ϕ' [deg]	FS [-]	LWC
-	32	1.27	I
0.0 B	32	1.27	I + II
		1.12	I + II + III
0.5 B	32	1.23	I + II
		1.25	I + II + III
1.0 B	32	1.23	I + II
		1.23	I + II + III
2.0 B	32	1.31	I + II
		1.30	I + II + III
-	28	1.09	I
1.0 B	28	1.07	I + II
1.0 B	28	1.07	I + II + III

Tab. IX – Safety factors by FEM analyses of multiple level LWCs: influence of the vegetation growth, of the damage and of the local failure of the LWC at the base of the slope ($d = B$).
Tab. IX – Coefficienti di sicurezza dalle analisi FEM di palificate vive multiple (LWCs): influenza dell'accrescimento della vegetazione, del danneggiamento e del collasso della palificata di base (d = B).

State of the LWCs	FS [-]	LWC
Immediately after construction (intact)	1.23	I+II+III
4 years after construction	1.27	I+II+III
damage of the LWC at the base of the slope	1.22	I (damaged)+II+III
local failure of the LWC at the base of the slope	1.19	I (partial failure)+ II+III
	1.10	I (total failure)+ II+III

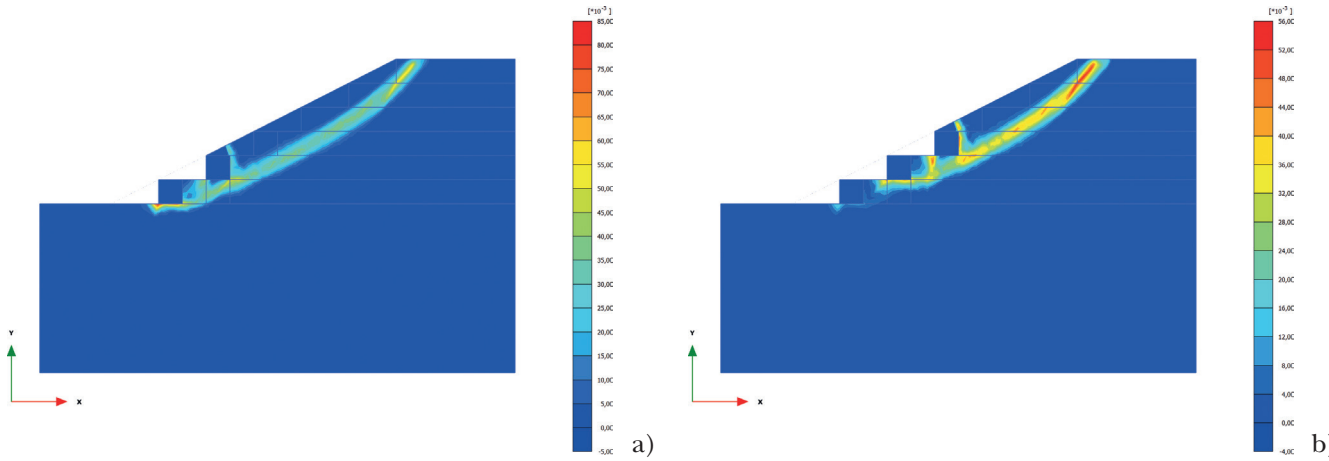


Fig. 14 – Safety analysis: total deviatoric strains with multiple LWCs ($d = B$). $\varphi' = 32°$. *a*) I + II LWCs; *b*) I + II + III LWCs.
Fig. 14 – Analisi di stabilità: deformazioni deviatoriche con palificate (LWCs) multiple ($d = B$). $\varphi' = 32°$. a) I + II LWCs; b) I + II + III LWCs.

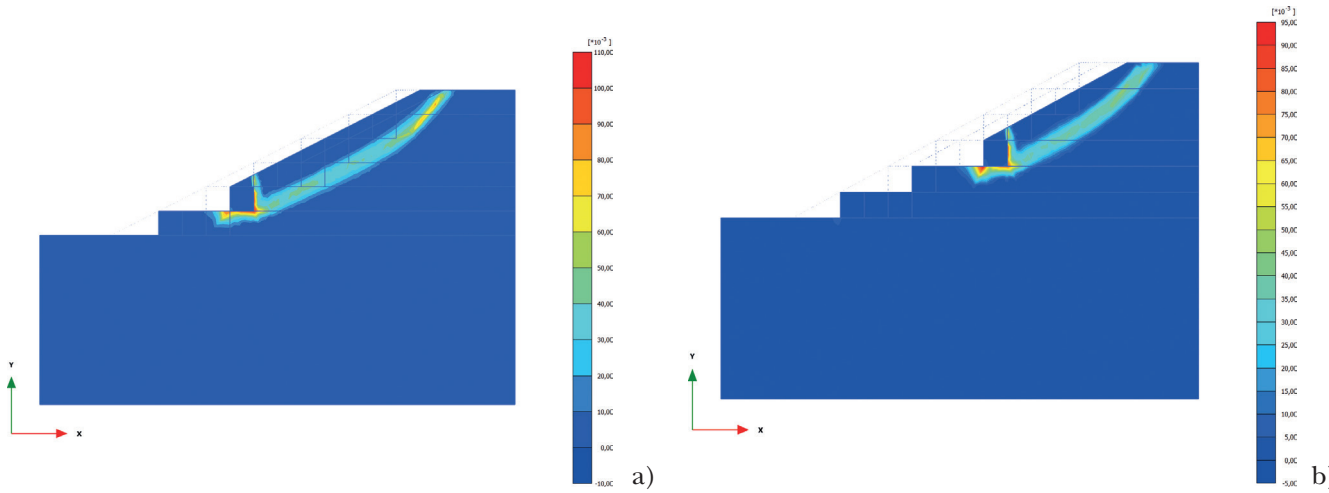


Fig. 15 – Safety analysis: total deviatoric strains with multiple LWCs ($d = 2B$). $\varphi' = 32°$. *a*) I + II LWCs; *b*) I + II + III LWCs.
Fig. 15 – Analisi di stabilità: deformazioni deviatoriche con palificate (LWCs) multiple ($d = 2B$). $\varphi' = 32°$. a) I + II LWCs; b) I + II + III LWCs.

re-profiling of the slope. The distribution of the maximum deviatoric strain inside the slope is also a valuable outcome of the FEM analysis. Figures 14 and 15 clearly show how potential failure surfaces intersect the LWCs and interact with them as the value of d/B decreases.

From this evidence, it appears that when values of $d/B \leq 1$ are adopted, the LWC cannot be verified as a single structure, at least in terms of global stability and for the present geometrical configuration. In fact, for these (small) values of d/B, all the cribwalls are interested by the potential failure mechanism. The same conclusions can be drawn assuming a soil friction angle equal to 28° (instead of 32°), as shown in figure 16.

In the attempt of considering the effect of the vegetation growth on the performance of multiple LWCs the global slope stability was investigated by improving the mechanical properties of the soil just behind the LWCs of the amount which can be expected after 4 years from the end of construction of the three LWCs (see section 3.2). Thus, behind each LWC, a zone of improved mechanical properties was considered in the model extended, at the fourth year, for a root depth L_R=2 m towards the slope (see the dotted areas in figure 17a), as suggested by the pertinent growth curve in figure 11.

As in the case discussed in section 3.2, five cuttings/meter are considered. The increase in shear strength provided by the roots was estimated by using Wu and Waldron's model considering the growth at the fourth year. Then the strength contribution offered by the roots was reduced by 75%, obtaining a root cohesion $\Delta\tau$~1 kPa.

The interaction between the LWCs appears only for $d/B \leq 1$ (see Fig. 17b). The safety factor, for the

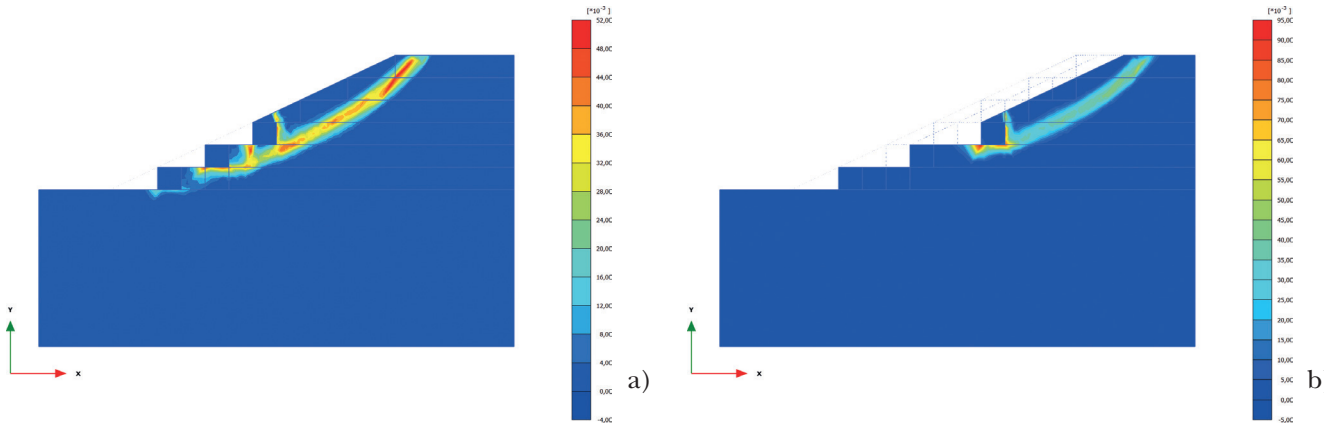


Fig. 16 – Safety analysis: total deviatoric strains with multiple LWCs ($d = B$ on the left and $d = 2B$ on the right). $\varphi' = 28°$.
Fig. 16 – Analisi di stabilità: deformazioni deviatoriche con palificate (LWCs) multiple (d = B a sinistra e d = 2B a destra). $\varphi' = 28°$.

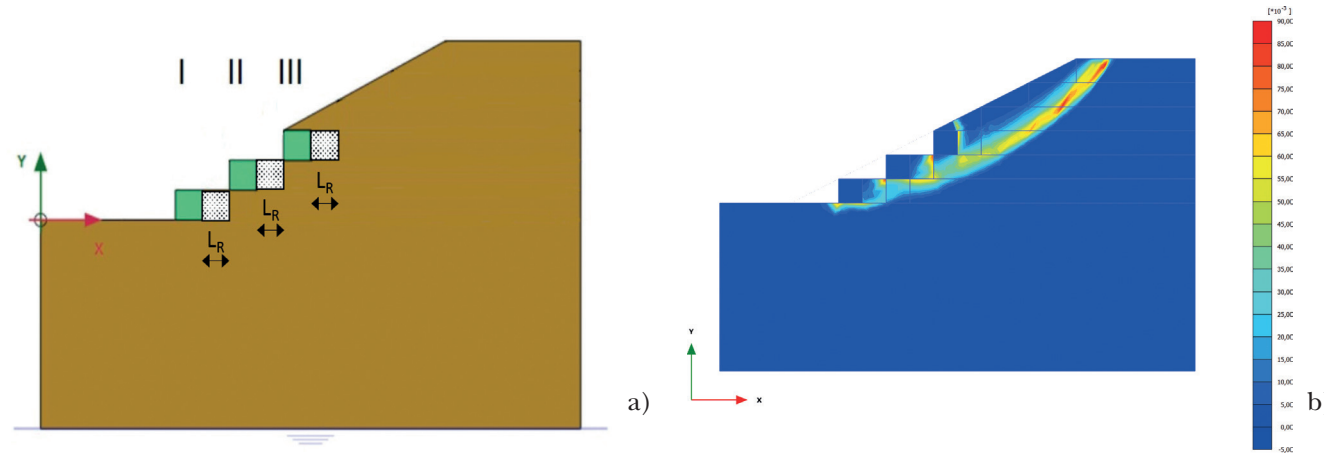


Fig. 17: *a*) Scheme of the slope used for the numerical model with indication of the extension L_R of the rooted areas (dotted zones); *b*) Safety analysis: total deviatoric strains with multiple LWCs ($d = B$) after 4 years from the installation of cuttings.
Fig. 17: a) Schema di pendio per le analisi numeriche con indicazione della zona di estensione delle radici L_R ; b) Analisi di stabilità: deformazioni deviatoriche con palificate (LWCs) multiple (d = B) dopo 4 anni dall'installazione delle talee.

case $d = B$, slightly increases passing from FS = 1.23 to FS = 1.27 in four years, (*i.e.* an increase of only 3%, see Tab. IX). Being a local effect of the root growth, this contribution increases the shear resistance behind individual LWCs, as shown in figure 17b: the shear stresses and strains are better sustained, without failure, right in those zones.

Finally, further FEM analyses were performed to investigate how a local instability mechanism of at least one LWC could influence the overall performance of multiple LWCs. Two possible mechanisms were simulated, assuming in both cases $d/B = 0.5$ and $d/B = 1$ (elements I, II and III are all present).

The first mechanism simulates a damage inside the cribwall, namely the emptying or degradation of the LWC material (soil, wooden logs, etc.). The values of the simulation parameters associated with the LWC were modified and are also reported in table VII.

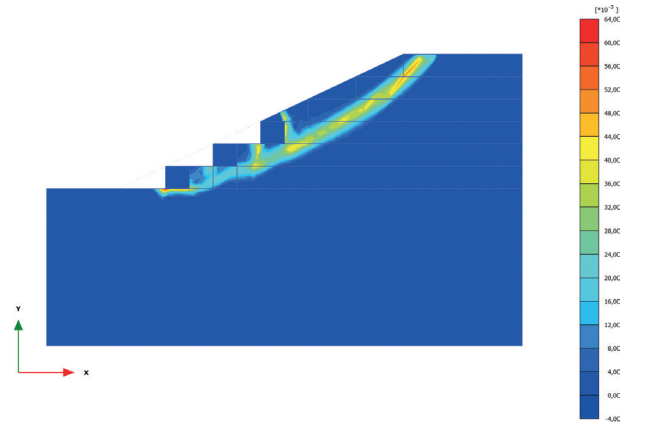


Fig. 18: Safety analysis: total deviatoric strains with multiple LWCs ($d = B$) with damage at the LWC n. I.
Fig. 18: Analisi di stabilità: deformazioni deviatoriche con palificate (LWCs) multiple (d = B) con danneggiamento sulla palificata LWC n. I.

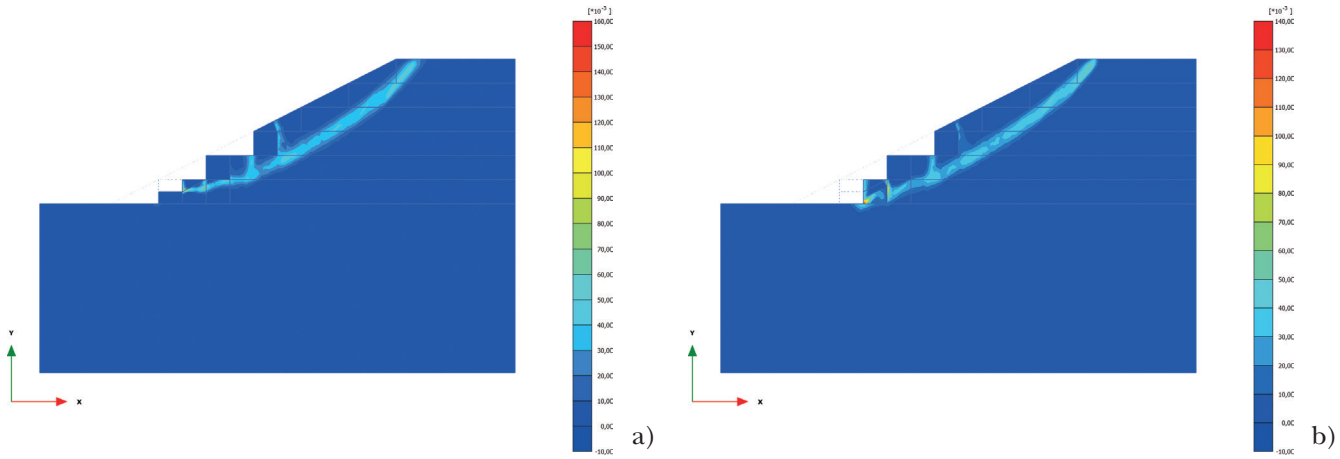


Fig. 19 – Safety analysis: total deviatoric strains with multiple LWCs ($d = B$) if LWC no. I *a*) partially failed or *b*) totally failed.
Fig. 19 – Analisi di stabilità: deformazioni deviatoriche con palificate (LWCs) multiple (d = B) con palificata LWC no. I a) parzialmente collassata; b) completamente collassata.

The second mechanism simulates a partial or total failure (*e.g.* sliding or overturning, see section 3.1) of the cribwall no. I, placed at the slope base. This mechanism was simulated, in the FEM analyses, by either partially or totally removing the LWC no. I. It is worthwhile to mention that in the FEM analyses, a fictitious thin layer of soil with cohesion and friction angle equal to 10 kPa and 32°, respectively, has been placed right behind the LWC no. I, in order to allow us to investigate the global stability of the entire slope, rather than a concentrated soil failure due to cribwall removal.

Table IX reports the values of the slope safety factor obtained with the FEM analysis: as expected *FS* decreases with respect to the undamaged case, the reduction being more severe for the cases of partial or total wall failure (second instability mechanism) than for the damage of the LWCs (first instability mechanism).

Also in these cases, all the LWCs placed along the slope are influenced if the relative spacing $d/B \leq 1$ (see figures18 and 19), the global stability of the slope being compromised.

On the basis of the simple numerical analyses presently performed, it should be advisable to adopt, at the base of the slope, cribwalls having a larger size than the ones placed along the slope. Similar indications were also provided by other investigators *(e.g.* see JALLA, 1999).

Concluding, this set of numerical analyses clearly show the importance of proper design, control and maintenance of single LWCs, especially when they are part of a slope stabilization system.

4. Concluding remarks

The employment of soil bio-engineering techniques to prevent the erosion or the failure of the soil along slopes can be considered as a reliable and sustainable alternative to traditional geotechnical works as long as the uncertainties that are unavoidably associated with the use of natural and live materials are considered and taken into account.

Almost all soil bio-engineering interventions suffer these limitations: the present contribution focuses on revegetation and live wooden cribwalls, which are two techniques widely used by practitioners.

As concerning revegetation, an experimental approach was adopted to investigate the mechanical action of roots on soil, being initially saturated or under a saturation process, in order to simulate natural conditions along a potentially unstable slope. The present description of the experimental results is an extension of the previous contribution of MAZZUOLI *et al.* [2016].

In the second part of the paper, the capabilities and the limits of live wooden cribwalls, which can be used to retain cuts few meters high, were investigated by means of parametric analyses.

The results of tensile tests on individual root filaments and of triaxial tests carried out on rooted soil samples are shown and discussed with the aim to identify the contribution of roots to the soil shear strength. A description of the special moulds used to make the samples of soil in which plants were let grow and develop their roots for a few months, was also provided. First, individual roots were tested with cyclic tensile loads and the mechanical behaviour of individual root filaments was found similar to that of elastomers (quantitatively similar to rubber). In particular, three phases during each test were identified which differ in the mechanical response of the filaments possibly associated with different stages of failure of the coaxial root shells. The strain of roots filaments before their failure was found relatively high (10% ÷ 20%), which explains why the displa-

cements of roots in the field are typically of the order of magnitude of a few centimeters. Indeed, the fact that the deformability of roots is much larger than that of soil is at odds with the hypothesis of Wu and Waldron's model, widely used to estimate the rooted-soil shear strength, which is based on the assumption that roots can mobilise their maximum resistance. Then, the action of roots naturally developed in sandy soil samples was measured by means of non-conventional triaxial tests. A stress path which mimics the soil condition of a vegetated slope during an intense rainfall was also implemented. It was found that, if roots were homogeneously distributed in the soil sample and occupied at least the ~4% of the total volume, the action of roots manifested itself in a significant reduction of the tendency of the sample to dilate, especially for large strain levels, which resulted in the contextual increase of the pore pressure and of the deviatoric stress that the sample could resist. To the knowledge of the authors, this is the first time that the contribution of roots was isolated from the response of a sample naturally rooted, subject to triaxial compression. Further experimental results are now required to move from the finite-volume scale to the field scale and reliably to model the soil-root interaction.

The support that live plants can supply to the soil through their roots can be exploited to build live wooden cribwalls, which are considered one of the most effective soil bio-engineering retaining structures. The advantages of LWCs with respect to other similar works, limitations and frequent design (and execution) errors are remarked. LWCs, are presently described as a geotechnical engineering technique, because their design should not be based on empirical rules, but on geotechnical calculations and analyses which verify the current technical regulations. Following this approach, parametric analyses have been performed aimed at estimating the safety factor with respect to external stability. On the basis of the values of the safety factor (which were estimated by considering sliding and overturning mechanisms and the bearing capacity of LWCs), it is shown that, at the preliminary stage of design, the height of cribwalls can be assumed equal to their width. This confirms an empirical rule adopted by practitioners since a long time, which, however, can be too conservative. Indeed, for a given set of values of the geotechnical soil parameters, smaller values of the ratio *B/H* can be safely attained by modifying the cribwall geometry and taking advantage of vegetation growth. In fact, vegetation suitably installed into the wall face, can significantly improve the stability of the structure in the long term, since plants develop deeper roots that provide the soil with a natural reinforcement. Proper design should take the benefits associated with the evolutionary aspects of vegetation into account. The evolutionary analysis of LWC stability requires that plant growth parameters are available, assuming that vegetation develops "fittingly", which introduces further uncertainties. In any case, it is advisable to reduce, even significantly, the estimate of the contribution of roots to the soil strength.

Multiple LWCs (of the same size) can be assembled to form step-like retaining structures which are often used also to re-profile potentially unstable slopes. Presently, the stability analysis of multiple LWCs was performed by numerical means in order to identify a criterion to quantify the spacing between the cribwalls and to investigate the role of the functionality and integrity of the base cribwall in the stability of the entire retaining system. It was found that a value of the relative spacing $d/B > 1$ is advisable. Indeed, for smaller values, LWCs can no longer be designed as single elements, because the mutual interaction between the structures is significant and should be taken into account.

It was also showed that the evolutionary aspects of wood, the emptying of the soil inside the cribwall and any degradation of the structure, leading eventually to possible failure mechanisms, should be consider to achieve an accurate design.

Moreover, it is strongly encouraged to check LWCs for internal failures, as otherwise required by current regulations for this kind of mixed retaining walls.

In conclusion, LWCs can be effective retaining walls, especially in natural contexts, provided that geometry constraints, design calculations, construction phases and the proper maintenance of vegetation are carefully considered.

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Interventi di ingegneria naturalistica per la protezione dei versanti e la prevenzione di frane superficiali

Le tecniche di ingegneria naturalistica fanno uso di piante, eventualmente combinate a strutture in legno, per proteggere e rinforzare il suolo e al contempo conferire un aspetto naturale ad aree antropizzate. Sono spesso adottate, laddove possibile, in luogo di interventi tradizionali di ingegneria geotecnica, traendone benefici in termini ecologici ed economici; tuttavia, per una opportuna progettazione, sono necessarie conoscenze più dettagliate e rigorose riguardo la loro effettiva risposta meccanica. Il presente contributo è stato sviluppato nel contesto di un progetto di ricerca incentrato sulla mitigazione del rischio da frana con interventi sostenibili, ed è diviso in due parti. Nella prima parte, dopo una breve panoramica sulle pratiche di ingegneria naturalistica più comunemente utilizzate, sono descritti e discussi i risultati di una serie di prove di laboratorio condotte sia su radici di piante sia su campioni di suolo radicato in cella triassiale. Nel presente contributo è identificata, a scala di elemento di volume, l'azione meccanica delle radici su un terreno sabbioso saturo sottoposto a sforzi di taglio. I risultati evidenziano come il contributo delle radici, significativo in quasi in tutte le applicazioni di ingegneria naturalistica, risulti fondamentale per le tecniche di rivegetazione. Sono inoltre evidenziati i vantaggi e i limiti del modello di Wu e Waldron, usato frequentemente per stimare il contributo di resistenza al taglio offerto al terreno dalle radici. La seconda parte dell'articolo è dedicata alla descrizione della tecnica delle palificate vive, in modo da fornire informazioni generali per un uso consapevole di questa tecnica naturalistica, finalizzata a sostenere fronti di scavo in coltri di modesto spessore e garantire la stabilità nei confronti di movimenti superficiali di versante. Il contributo meccanico delle piante, con il loro accrescimento che migliora progressivamente l'efficacia delle palificate vive, è mostrato in termini di incremento del fattore di sicurezza globale, valutato con analisi numeriche.