Mechanical and hydraulic effects of deep roots planting on slope stability

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ABSTRACT: Slope vegetation is currently finding wide applications all over the world to mitigate erosive phenomena and improve slope stability. An innovative natural technology for slope protection has been recently developed in Italy; this uses only natural perennial grass plants with deep roots and allows operating in different climatic areas. The technology appears promising with regard to shallow slope instability. The mechanical effects of vegetation result from the root/soil interaction processes, while the hydraulic effects derive from the reduction of soil water content enhanced by plant transpiration and root uptake. An original model is proposed in the paper to take into account the mechanical effects on the soil shear strength; the main assumption of the model regards the function developed for the root area ratio. The research sets as a final goal the quantitative assessment of both mechanical and hydraulic effects induced by roots on slope stability.

1 INTRODUCTION

Over the years and in different world areas, many techniques of slope protection and re-naturalization have been developed. Slope vegetation represents a quite innovative technique for the control and mitigation of water erosion phenomena and, contextually, may play a positive role in slope stability by simply considering that the plant roots act as special soil reinforcement. This aspect of soil vegetation gains much importance provided that herbaceous deep-roots - with high tensile strength properties - are well seated into the soil.

The role of vegetation in slope protection from erosion phenomena has been studied and documented throughout experimental investigations. Several approaches - based on theoretical models, physical or empirical models - have been proposed in the literature for the quantitative evaluation of erosion (soil loss). Among these, it is worth to cite the *Universal Soil Loss Equation* - USLE (Wischmeier, 1976; Wischmeier and Smith, 1978). Amongst the consolidated techniques aimed at reducing soil and rock erosion developed in the years 1950-’60 and involving the use of manufactured products such as geonets, geogrids, fascines, special interest is to be paid to herbaceous plants characterized by deep roots - with great length (3 m) and extraordinary tensile strength - which may contribute to reduce erosion. In particular, the aerial portion of such herbaceous grassy plants dissipates most of kinetic energy of rain drops, smoothing their erosive action; moreover, even when the plants are seasonally dried up, an important fraction of rain flows above the aerial portion of the vegetation in case of intense rainfalls. This eco-technique, obtained by seeding perennial herbaceous plants directly into the soil, is of simple and fast installation and does not require any maintenance. Recent studies, also supported by botanists, agronomists, naturalists and geologists, have highlighted the ability of many herbaceous species to effectively contrast erosive phenomena, even in bare and sterile soils where other common species do not succeed to vegetate.

The implantation of grassy species, made of deep and thin roots with large tensile strength, may represent an interesting technique also for the improvement of slope equilibrium conditions, limitedly to *shallow* and potentially unstable soil masses. In order to assess the additional important role played by slope vegetation, the soil-roots interaction needs to be specifically analyzed from a *mechanical* and a *hydraulic* point of view. Some of these aspects are dealt with in the following paragraphs. The subject is complex since several phenomena are involved in the soil/vegetation interaction and their study requires specific skills in various fields such as hydraulics, agronomy, soil physics, in addition to soil mechanics. From a theoretical point of view, the mass balance equations must be respected in the position of the problem, by taking into due consideration the concurring phenomena of soil evaporation, plant transpiration, water runoff along the slope, water infiltration into the soil and water uptake from roots. In fact, the root system may affect the hydrologic balance, due to the capacity of the aerial plant system to reduce water infiltration and soil water content; the latter reduction causes a further increase in soil shear strength. The Authors have recently started a comprehensive study aimed at numerical modeling the soil-root interaction from both mechanical and hydraulic points of view. The research is motivated by the need of improving the comprehension of such concurring phenomena.

The next paragraph is devoted to specifically analyze the *mechanical* effects of deep roots planting on slope stability, while the hydraulic effects will be dealt with in the following sections.

2 SOIL-ROOTS MECHANICAL INTERACTION

As well-known from the specialized literature, the roots system generally favors the increase of soil shear strength within the rooted layer (Wu, 1976; Waldron, 1977; Gray and Leiser, 1989; Gray and Sotir, 1996; Wang and Lee, 1998; Bischetti, 2000; Qi and Hu, 2006). This improvement mainly depends on two different processes:

- the positive role of plant roots acting as a mechanical soil reinforcement;
- the beneficial influence upon the hydrologic balance of the involved area, due to both the capacity of the aerial plant apparatus to capture (and redirect) part of the rainfall, and to the ability of the whole plant system to absorb water from the surrounding soil and transfer it to the atmosphere through transpiration (root water uptake). The latter mechanism may yield to an increase of suction and, as a consequence, of the soil shear strength (Vanapalli et al., 1996; Wan et al., 2011).

In the 70's, Wu (1976) and Waldron (1977) have proposed a simple mechanical model for the single root embedded into the soil, assuming that the root behaves like a linear cylindrical fiber of high tensile strength.

According to this approach, the increase of soil shear strength offered by the root, $\Delta\tau_r$, is a function of the root tensile strength, t_r, the soil friction angle, ϕ , and the ratio between roots cross section, A_r, and the rooted soil cross section, A_{rs}. The generalization of the problem - faced for the single root - to the whole root-system permeating the soil, results into Equation (1):

$$\Delta\tau_r(z) = k \cdot t_r \cdot \frac{A_r(z)}{A_{rs}} \quad (1)$$

where k is an non-dimensional empirical factor which is assumed to depend on the plant *specie*. The root tensile strength, t_r, entering Equation (1) can be evaluated through experimental tensile tests. Data obtained from tests on several variants of perennial grassy species, mainly belonging to the botanical families of *Graminacae* and *Leguminosae* (Bonfanti and Bischetti, 2009) clearly show that t_r sensibly decreases with increasing root diameter, d, and may attain extremely high values (tens of MPa) for a root diameter of about 0.5-1.5 mm. For such roots, the experimental data can be successfully fitted through power functions of the type:

$$t_r[MPa] = a \cdot d^{-b} \quad \text{with } d \text{ [mm]} \quad (2)$$

where parameters a and b only depend on the plant *species* (Cecconi et al., 2012).

2.1 *Root area ratio*

In Equation (1), the quantity A_r/A_{rs} represents the ratio between the rooted-area, A_r, and the rooted soil cross-section area, A_{rs}. The ratio A_r/A_{rs} is also denoted as "root area ratio, *RAR*" and typically decreases with depth; this occurrence is generally verified despite of the complex geometry of the root system which presents a great variability depending on plant species, soil properties and profile, but also climatic and environmental conditions (*e.g.*: Abe and Ziemer, 1991; Feddes et al., 2001; Osman and Barakbah, 2006; Zuo et al., 2004; Preti et al., 2010). Due to such intrinsic variability, the evaluation of the root area ratio requires careful attention. To give an example, Preti et al. (2010) have proposed for both $A_r(z)$ and ratio $RAR(z)$ an exponentially decreasing function with depth z.

In this study, the evaluation of root area ratio for herbaceous deep-roots is based on the geometrical model schematically shown in Figure 1 and originally proposed by Cecconi et al. (2012) for fasciculate root systems. The geometry consists of a truncated cone with opening angle, β (generally varying in the range 10-15°), surface radius, r, and maximum radius R attained at maximum depth $z_{r,max}$. Every single root has diameter, d_i, and cross section, $a_{r,i}$. The maximum value of the root area ratio, RAR_{max}, is found at the ground surface. At any depth z from the ground table, the rooted area, $A_r(z)$ may be given by:

$$A_r(z) = \sum_{i=1}^{m} n(z, d_i) \cdot a_{r,i} \quad (3)$$

In Equation (3), the number of roots $n(z, d_i)$ varies with depth and root diameter; in fact, usually some of the roots do not reach the maximum depth $z_{r,max}$.

Thus, in order to evaluate the *RAR* profile with depth, quantities A_{rs} and $A_r(z)$ have to be calculated. From a numerical point of view, $A_r(z)$, has been calculated by firstly dividing the maximum root depth, $z_{r,max}$, into 25 layers 10-30 cm in thickness (depending on $z_{r,max}$), and then assigning, for each layer, m classes of different diameter. To this aim, a random function generates the root number $n(z,d_i)$ for each discretized layer and root diameter. Maximum values of n are approximately set for each meter of

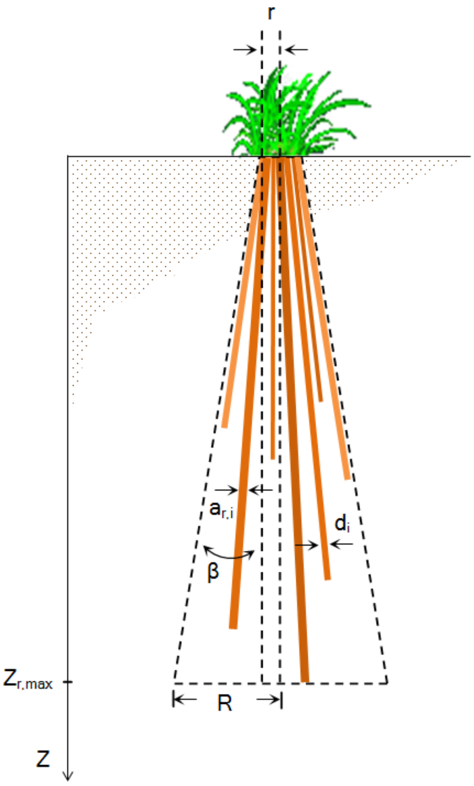


Figure 1: Geometrical model for fasciculate root systems (from Cecconi et al., 2012).

depth, by simply considering that for a single fasciculate root-system the number of roots decreases with depth. From the available experimental evidence, reasonable values of n vary from n_{max} = 40 in the top layer, down to $n_{\min}$ = 10 at 2-3 m of depth. Then, by considering that, presumably, the number of fasciculate root systems in a 1m^2 soil area is about $10 \div 30$, the maximum rooted area A_r, at ground table ($z=0$), is approximately $A_{r,0}$=2000 mm^2 for each 1m^2 soil area.

At this point, for simplicity, it is convenient to assume a constant rooted soil volume, A_{rs}; to do that, the truncated cone is assimilated to a rooted soil cylinder of equivalent radius R^*, *i.e.*:

$$R^* = r^2 + r z_{r,max} \tan\beta + \frac{1}{3}(z_{r,max} \tan\beta)^2 \tag{4}$$

In a 1m^2 reference rooted soil area, as the one considered in a stability analysis performed with the *infinite slope* method (see §2.2), one obtains:

$$A_{rs} = \pi \cdot R^{*2} = 1m \cdot 1m \rightarrow R^* = 0.5642\,m.$$

Values of $A_{r,0}$ and A_{rs} yield to ratio RAR at ground table, $RAR_{max} \cong 0.2\%$, in agreement with other data available in the literature for similar herbaceous deep roots (Bischetti, 2000).

As an example, Figure 2 shows for *Eragrass species* deep-roots the calculated distribution (Fig. 2a) of rooted area $A_r(z)$ and the corresponding estimated RAR profile (Fig. 2b). Although the longest roots could even reach 3 m of depth, the RAR value

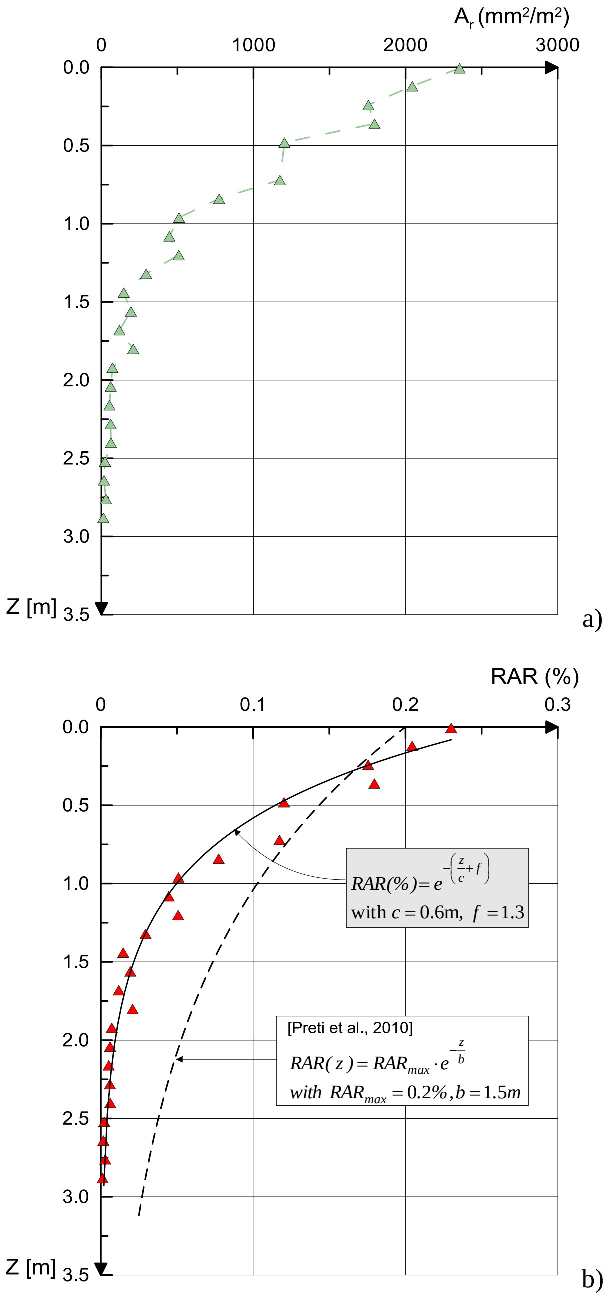


Figure 2. Fasciculate deep roots of Eragrass species: numerical results showing a) the distribution of $A_r(z)$ with depth z and b) the obtained RAR profile.

becomes negligible at much smaller depths (1.5 – 2 m). The analytical function proposed by Preti et al (2010) to describe the RAR profile is also plotted in Figure 2b:

$$RAR(z) = RAR_{max} \cdot e^{-\frac{z}{b}} \tag{5}$$

having assigned RAR_{max} = 0.2% and b = 1.5m (average rooting depth); a relatively poor agreement is found between the two distributions. On the contrary, the $RAR(z)$ profile proposed herein appears to be better described by the following function:

$$RAR(\%) = e^{-\left(\frac{z}{c}+f\right)} \tag{6}$$

with $c = 0.6\text{m}$, $f = 1.3$.

2.2 *Shear strength increase from deep-roots*

The maximum increase in soil shear strength provided by the roots, $\Delta\tau_r(z)$, has been derived by extending the application of Equation (1) to a heterogeneous roots system as follows:

$$\Delta\tau_r(z) = RAR(z)\cdot\sum_{i=1}^{n}\left(t_{r,i}\cos\theta\cdot\tan\phi + t_{r,i}sen\theta\right) \qquad (7)$$

In Equation (7), $t_{r,i}$ is the root tensile strength (for a root diameter d_i) and θ is the angle of shear distortion of a single root crossing a potential shear surface (see Figure 3).

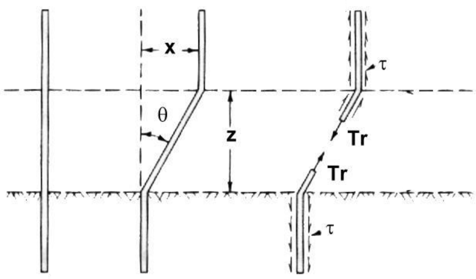


Figure 3: Single root crossing a shear surface: angle of shear distortion θ (from Gray and Ohashi, 1983).

In any case, in order to use Equation (7), a minimum root length, l_{min}, is required to avoid the occurrence of slippage before root tensile failure (see Waldron, 1977). In fact, the roots embedment must be sufficiently large, so that the frictional resistance at the soil/root interface could exceed the tensile root strength and prevent pull-out of the root itself. By assuming each single root to a cylindrical elastic fiber (Gray & Leiser, 1989), the minimum root embedment l_f is given by Equation (8):

$$l_{min} = \frac{t_r d_r}{2\tau_{pr}} \qquad (8)$$

If root lengths are shorter than $l_{\min}$, the root will slip or pull-out before tensile failure could occur. In Equation (8), τ_{pr} is the maximum shear stress at the soil/root contact.

In this work, equation (7) has been applied in order to quantify the mechanical effects of embedded deep roots on slope equilibrium conditions. To this aim, slopes with relatively shallow (1-1.5 m) soil coverings underlain by a stiffer stratum may provide a good case study; this problem can be considered as one-dimensional and can be modeled through the *infinite slope* method.

By taking into account the mechanical effects of the deep roots, the safety factor SF_r for a soil cover with friction angle ϕ' and cohesion *c'*, is given by:

$$SF_r = \frac{\tau_f + \Delta\tau_r}{\gamma z\cdot\cos\alpha\cdot sen\alpha} = \left(1-\frac{\gamma_w\cdot D_w}{\gamma z}\right)\cdot\frac{\tan\phi}{\tan\alpha}+\frac{c'+\Delta\tau_r}{\gamma z\cdot\cos\alpha\cdot sen\alpha} \qquad (9)$$

where α is the slope angle, while z and D_w are respectively the depth of the potential shear surface and the distance between this depth and the water table, if present ($D_w \geq 0$). In the following, the simple case of a root-permeated slope of cohesionless pyroclastic soils above water table (classified as sands, ϕ' = 38°, *c'* = 0) is considered. The average slope angle is rather large, α = 30°, and the root systems consist of *Eragrass species,* with an average root diameter d = 0.66 mm (d_{min} = 0.24mm, d_{max} = 1.08 mm) and a maximum root depth $z_{r,max}$ = 3 m.

The results of the slope stability analysis are shown in Figure 4. The calculated *RAR(z)* profile shown in Figure 2b leads – through Equations (7, 9) - to the profiles $\Delta\tau_r$ and SF_r plotted in Figures 4a and 4b (green triangles). The favorable root effect is put in evidence in Figure 4b, when the calculated values of the factors of safety are compared to those pertaining to a slightly cemented soil (*c'* = 5kPa, 10kPa), in the absence of roots; the vertical line denotes the critical value *SF* = 1.35 obtained for *c'*= 0.

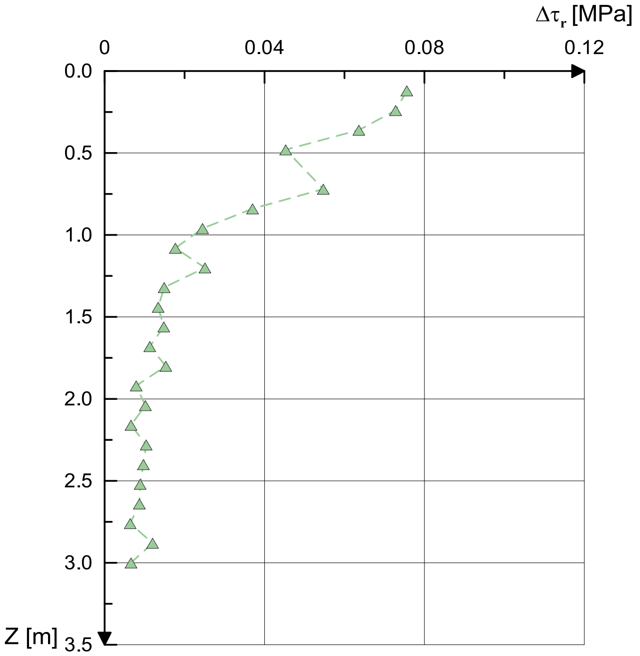
The mechanical effect of roots leads to a noticeable increase of *SF*: in particular, such increase is comparable - in the upper 1 – 2.5 m - to the one induced, by an increase of cohesion (for a not-rooted soil) of about 10kPa; at larger depths the effects of roots becomes less noticeable for engineering purposes. Large values of *SF* calculated at very small depths (< 0.75 m) have not been plotted, due to their scatter and their small practical significance.

3. SOIL ROOT INTERACTION: HYDRAULIC EFFECTS

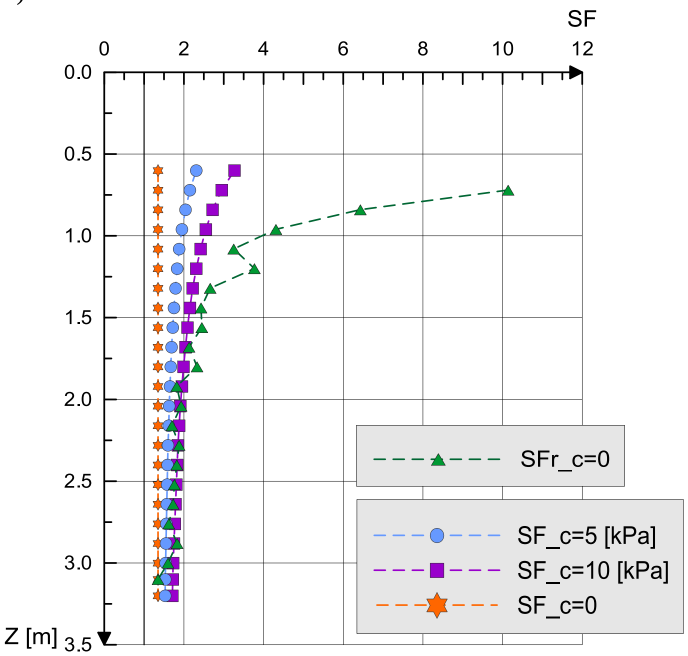
The analysis of the hydraulic effects in the soil-root interaction is very complex to understand and model. In this section, a position of the problem is outlined, on accounting for different occurring phenomena of plants evapo-transpiration, water infiltration into the soil, water runoff along the slope. Following Blight (2003), the soil water balance equation in the vadose zone can be symbolically written as:

$$\sum_{\Delta t}(R-IC)-\sum_{\Delta t}RO=\sum_{\Delta t}ET+S+RE+L \qquad (10)$$

where, over the reference time Δt, *R* is the total rainfall, *IC* represents the rainfall intercepted by vegetation, *RO* is the runoff, *ET* indicates the evapo-transpiration from the shallow subsoil, *S* is the water stored in the soil and *RE* represents any water flow through the vadose zone. The term *L* in Equation (10) is introduced by Blight (2003) to take into



a)



b)

Figure 4: Effects of root reinforcement on slope stability; profiles: a) $\Delta\tau_r$ *vs.* depth *z*; b) safety factor *SF vs. z*

account any inaccuracies in the measurements or in the position of boundary conditions.

The complete evaluation of Equation (10) requires available data for each of the six terms. The problem is thus very complex and, generally, Equation (10) is used to find one of the cited quantities, starting from the knowledge of the remaining ones.

3.1 *Interception*

When soil vegetation is made of deep herbaceous roots, like those examined in the present study (*e.g. Eragrass* fasciculate roots), the quantity *IC* requires to be better investigated. For example, this quantity can be evaluated from the simple relationship proposed by Morgan & Rickson (1995):

$$IC = CC \cdot R\cos\alpha \tag{11}$$

where α is the slope angle and CC is the aerial percentage of vegetation cover which, for herbaceous plants, can very high. Within the above quantity *IC*, a portion of the intercepted water, IC_{store}, is stored on the leaves and may later evaporate, while another portion, denoted in the literature as *temporarily intercepted throughfall, TIF*, reaches the ground as stem-flow, *SF*, or leaf drainage, *LD*, *i.e:*

$$IC = IC_{store} + TIF \tag{12a}$$

$$TIF = SF + LD \tag{12b}$$

With similar considerations, in the soil water balance equation the following quantities could be made explicit, for example, in the form:

$$ET = ET_1 + ET_2$$

$$RO = RO_1 + RO_2$$

where ET_1 is the actual evapotranspiration, ET_2 derives from the water stored on the leaves and then conveyed to the atmosphere; RO_1 represents the runoff of water reaching directly the soil and RO_2 the induced runoff from water temporarily intercepted by vegetation and then released to soil through stemflow or leaf drainage.

For the considered vegetation type (grassy deep roots), the interception storage IC_{store}, which may attain its maximum value $IC_{\max}$, can be evaluated through the following equation (Morgan & Rickson, 1995; Merriam, 1973):

$$IC_{store} = IC_{max}\left(1 - e^{-\frac{R_{cum}}{IC_{max}}}\right) \tag{13}$$

where R_{cum} is the cumulative measured rain in the reference time; however, for grassy covers IC_{max} does not exceed 1.2 – 2.5mm. From Equation (11) and (12a) it is then possible to compute the *TIF* amount of water and evaluate the stemflow *SF* according to (van Elewijck, 1988):

$$SF = TIF \cdot (\cos\vartheta \cdot sen^2\vartheta) \tag{14}$$

where ϑ is the average angle of the plant stems with respect to ground. Finally, the leaf drainage *LD* can be simply calculated through Equation (12b). In particular, for herbaceous deep-roots, the angle ϑ can be very small, rendering *TIF* approximately equal to the leaf drainage *LD*.

3.2 *Water uptake*

For the evaluation of the left side of the mass balance Equation (10) – globally representing the water infiltration into the subsoil - different approaches can be followed: empirical equations, physically-based simplified models and theoretical models including those based on the Richards equation applied to the unsaturated soil. When the water uptake by transpiring roots from the surrounding soil is also taken into account, the Richards equation (1931) can be reformulated according to the equation proposed by Mathur and Rao (1999):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left(K(h)\frac{\partial h}{\partial z} + K(h) \right) - S(z,t) \tag{15}$$

in which θ is the volumetric water content, *h* is the total hydraulic head and *K*(*h*) is the soil hydraulic conductivity. The quantity *S(z,t)*, denoted as the *sink* term (volumetric water content removed per unit time) mainly depends on the soil water content, on the root density profile and the potential transpiration rate (Feddes et al., 1976; Prasad, 1988).

Many *sink term* functions have been developed in the literature. Some of them are based on the assumption that the rate of transpiration may equal the whole water uptake throughout the *RAR* profile, i.e.:

$$S(z,t) = C(z,t) \cdot TR \tag{16}$$

where *TR* is the plant transpiration rate and *C(z,t)* is a weighing factor depending on the root length density function, water content profile and more generally soil water retention properties.

In this study, the function adopted for *C(z,t)* is the one proposed by Selim and Iskandar (1978):

$$C(z,t) = \frac{K(h) \cdot L(z)}{\int_0^{z_{r\,max}} K(h) \cdot L(z)dz} \quad , \quad \int_0^{z_{r\,max}} C(z,t)dz = 1 \tag{17}$$

in which *L(z)* [cm/cm^3] is the root length density function.

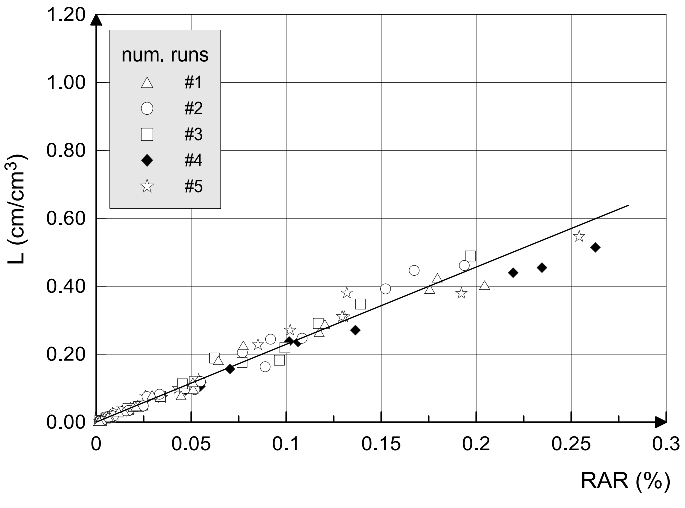


Figure 5: Calculated root length density function *vs.* RAR (*Eragrass species*)

As a first assumption, *L(z)* has been simply calculated by dividing the maximum root depth, $z_{r,max}$, into 25 layers of 10-30 cm in thickness (h_i), and then assuming the incidence of a roots number $n(z,d_i)$ for the total layer thickness. By so doing, one obtains:

$$L(z) = \frac{\sum_{i=1}^{m} n(z,d_i) \cdot h_i}{z_{r\,max} \cdot A_{rs}} \tag{18}$$

Similarly to the cited procedure adopted for the evaluation of the *RAR(z)* profile, a random function generates the root number $n(z,d_i)$ for each discretized layer and root diameter. As an example, the obtained distribution of *L(z)* is plotted as a function of *RAR(z)* in Figure 5.

Finally, looking again at Equation (10), the evapo-transpiration (*ET*) term – entering the right side of the equation - depends on vegetation type, climatic conditions, soil characteristics, and it is certainly complex to calculate; this challenge is beyond the scope of this study. It is sufficient to remind that for a quantitative assessment of evapo-transpiration the FAO-Penman-Monteith method (Allen et al., 1998) is often used, based on the daily “reference evapo-transpiration” (ET_0):

$$ET = (k_{cb} + k_e) \cdot ET_0 \tag{19}$$

where the *k* coefficients respectively quantify the transpiration capacity of the plant throughout the growth period, and the soil evaporation capacity as a function of the last rainfall event and soil vegetation. The product $k_{cb}ET_0$ represents the daily transpiration *TR* [mm/d], see Eq. 16.

4. AN EXAMPLE OF STABILITY ANALYSIS FOR A ROOT-PERMEATED SOIL

This paragraph is devoted to illustrate the results obtained from a numerical example of application, aimed at highlighting the mechanical and hydraulic effects of deep roots planting on slope stability conditions. The case study pointed out in previous section 2.2 of a root-permeated slope (α = 30°) of pyroclastic soils (ϕ' = 38°, *c'* = 0) is again considered. The root systems consist of *Eragrass species* (average root *d* = 0.66 mm and $z_{r,max}$ = 3 m). For this example, the assumed initial distributions with depth of soil suction (*s*) and volumetric water content (θ) are those shown with open symbols in Figure 6a and 6b, respectively. The high value of initial water content, near to initial saturated conditions, is consistent with the high porosity of pyroclastic covers (≅ 70%). Once the position of the problem is stated, in order to assess - with the above approximations - the mechanical and hydraulic effects of roots on slope stability it is possible to follow the calculation steps below:

- compute the daily transpiration rate through the FAO-Penman-Monteith method;
- estimate the root water uptake with Equations (16), (17), (18) and (19). By so doing, a new

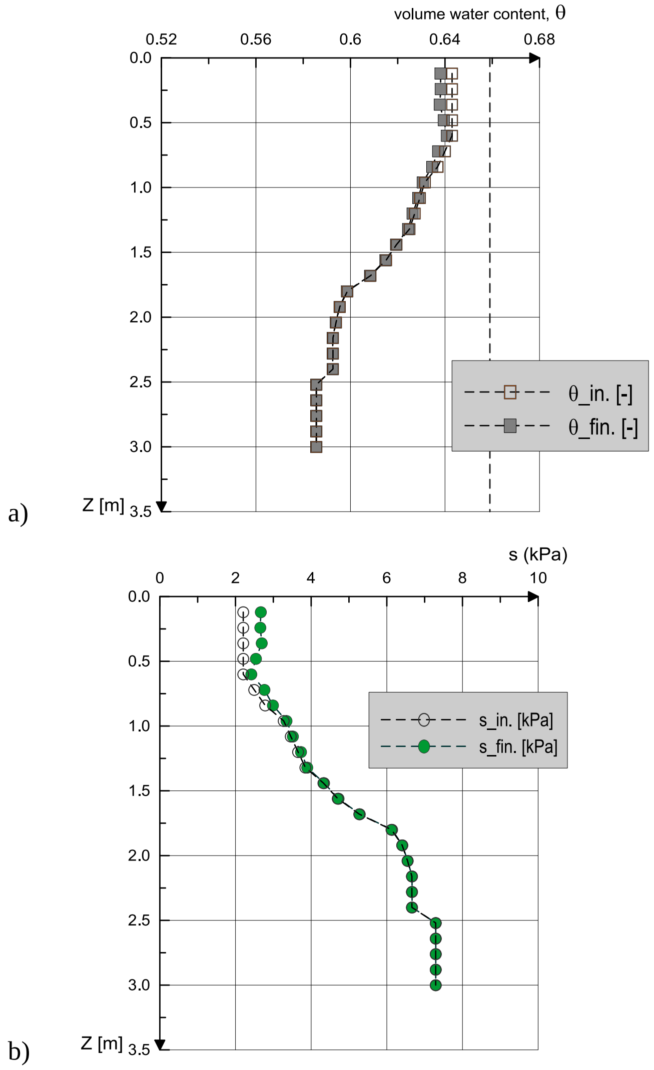


Figure 6. Effects of root water uptake on a) volumetric water content and b) suction profiles (sandy soil, Eragrass root species)

volumetric water content profile, $\theta(z)$, is obtained, as the one plotted in Figure 6a with full symbols. Note that in this example, $\theta(z)$ represents an average daily value;

- the definition of a proper soil-water retention curve ($\theta = f(s)$) for the considered soil (*e.g.*: Fredlund & Xing, 1994; Van Genuchten, 1980) allows the evaluation of a modified suction profile from the rooted-soil, as shown in Figure 6b;
- finally, an extended Mohr-Coulomb failure criterion for unsaturated soils (*e.g.*: Vanapalli et al., 1996) allows the evaluation of the shear strength of the unsaturated soil, thus also accounting for the presence of soil vegetation.

For the case study at hand, by modeling the slope through the *infinite slope* method, the safety factor SF_r for a soil cover can be written as follows:

$$SF_r(z) = \frac{\tau_{unsat}(z) + \Delta\tau_r(z)}{\gamma z \cdot \cos\alpha \cdot \sin\alpha} = \left(1 + \frac{S_r(z) \cdot s(z)}{\gamma z \cos^2\alpha}\right) \cdot \frac{\tan\phi}{\tan\alpha} + \frac{c' + \Delta\tau_r(z)}{\gamma z \cdot \cos\alpha \cdot \sin\alpha} \tag{20}$$

The numerical results of the slope stability analysis are shown in Figure 7, which shows the increase of the safety factor, ΔSF, with respect to that calculated for the not-rooted soil. Two different scales are used in the diagram to plot the data. The *hydraulic relative increase* of safety factor, $\Delta SF_h/SF$, is referred to the upper scale while the *total changes* in the safety factor (mechanical + hydraulic, $\Delta SF/SF$) are plotted in relation to the bottom scale. Note that, although both profiles decrease with depth, the two scales *in abscissa* differ of two orders of magnitudes. This implies that, for the considered problem, the prevailing effect of roots on slope equilibrium is the mechanical one.

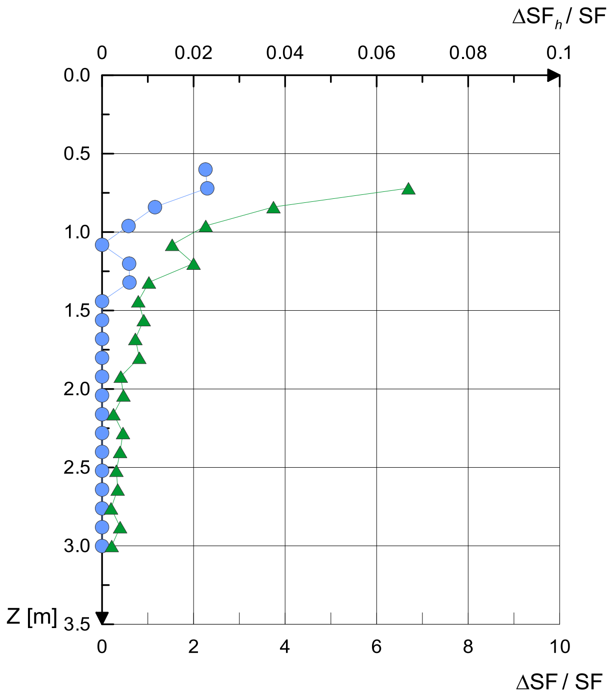


Figure 7. Increase of safety factor (ΔSF): root water uptake effects (blu circles) and coupled hydraulic and mechanical effects (green triangles) of deep roots on slope stability

5. CONCLUDING REMARKS

Erosion phenomena and surface slope instability may be effectively mitigated by vegetation with deep root systems. Such technology - consisting of seeding high-strength roots of perennial herbaceous plants - appears to be effective, simple and maintenance-free. The increase in soil shear strength mainly depends on the mechanical reinforcement induced by roots; however this positive role is limited to quite shallow slope covers (1 – 2m). A further contribute to soil shear strength, although rather small, is given by water uptake from roots and consequent increase of soil suction. A typical example of the described technique is given in Figure 8, showing a steep slope of weathered basaltic rock, before and after the grass roots planting. From the figure it is clear that the herbaceous species have effectively prevented surface erosion and re-naturalized the

a) b)

Figure 8: Example of slope vegetation through deep-roots planting (Central Italy): a) before planting; b) 18 months later

upper portion of the slope, despite of the lithological and morphological site conditions which could appear unfavorable to root embedding and growing.

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