Surface Protection of Slopes by Grass Covering Techniques

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Abstract Erosive phenomena are very diffused all over the world. Over the years different techniques of ground protection and renaturation have been developed. Among them, an outstanding and innovative natural technology uses only natural perennial grass plants with deep roots and allows to operate in areas where pedoclimatic conditions were until a few years ago considered prohibitive for the development of vegetation. Such technology also appears promising with respect to phenomena of surface instability of fronts: the deep root grasses may induce mechanical and hydraulic effects on slope equilibrium that typically increase the shear strength of soil. The mechanical effects of plant roots result from the root/soil interaction processes; the hydraulic effects derive from the significant reduction of water content and degree of saturation of soil caused by the presence of grass. Final goal of the research is the quantitative evaluation of such effects through modeling and implementation of a computing algorithm.

Keywords soil erosion phenomena, root planting, mechanical and hydraulic effects, surface protection of slopes.

Erosion phenomena

Dynamics of the erosive phenomena origin from various concomitant causes. On the Italian territory, mainly due to the climate characterizing our latitudes, the main erosive agent is represented by rain water that erodes the soil through various actions (hydraulic erosion) like:

- kinetic energy of water drops (drop erosion);
- soil particles superficial transport (interill erosion);
- formation of rivulets (rill erosion);
- formation of tracks and deep gullies (gully erosion).

The intensity of the erosive action then depends on several factors, like:

- intensity and duration of rain water;
- length and inclination of the slope;
- vegetation;
- intrinsic soil erodibility, mostly correlated to the granulometric characteristics of the soil itself.

The role of the vegetation in the protection of the slopes from the erosion has been long studied and documented by experimental investigations. The protection from erosion depends on the type of vegetation, arboreal and/or herbaceous, and in general terms it consists in:

- absorption of a part of the kinetic energy of the water drops;
- slowing down of the streaming phenomena;
- delay in the attainment of the conditions of complete soil saturation;
- soil reinforcement thanks to the root system;
- limitation, filtering and contrast of particles dragging phenomena.

Several approaches for quantitative evaluation of erosion (soil loss) have been proposed, like those based on theoretical models, physical models at reduced scale and empiric models. Among the last ones is evidenced the Universal Soil Loss Equation - USLE (Wischmeier and Smith, 1965; 1978), empirical equation adopted by United States Department of Agriculture for assessment of hydraulic erosion.

Such equation generally is diffused in the following form:

$$A = R \times K \times LS \times P \times C \qquad [1]$$

where:

A: specific soil loss [t/ha year], associated to phenomena of rill and interill erosion;
R: Rainfall-Runoff Erosivity Factor: climatic factor relevant to the intensity and duration of precipitations [MJ mm/ha h year];
K: Soil Erodibility Factor: pedologic factor that expresses the erodibility of the ground [t h/MJ mm];
LS: geometrical factor function of the steepness and length of the slope;
P: Supporting Practices Factor: reduction factor taking into account possible interventions of protection, control and conservation;
C: Cover-Management Factor: reduction factor depending on the vegetation.

Among the actions finalized at reducing erosion effects, special interest is to be paid to plants with deep roots and strong aboveground vegetation that may contribute to reduce factors P and C in equation [1].

The viable anti-erosive techniques currently more diffused go back to years 1950-60. They all imply the use of manufactured products like grid locks, geotextile meshes, drapery systems, faggots, wicker mats, etc. that nevertheless, in difficult pedoclimatic conditions, might not fully solve the erosion problem. Moreover, trees, shrubs and traditional meadows have been always employed in order to try to contrast erosion phenomena and possible small landslides.

More recent studies, also supported by botanists, agronomists, naturalists and geologists, highlighted the ability of some herbaceous species with deep roots to contrast very effectively the erosive phenomena, even in barren and sterile soil where species of normal usage do not succeed to vegetate.

Moreover, the realization of an anti-erosive system consisting only of vegetal material, obtained by directly seeding perennial herbaceous plants with deep root system directly on the soil as is, may be of simple and fast installation and does not require any maintenance.

The application field of these technologies, like the one developed in Italy by PRATI ARMATI srl, is rather wide: banks and ridges of roads and railways, embankments, quarries, waste dumps, sea facing areas, protection of river banks, water ways, artificial channels.

The behaviour of deep rooting grassy plants contrasting the above mentioned water erosion phenomena appears promising for the following reasons:

– the vegetation leaves dissipate most of kinetic energy of rain drops, thus smoothing their erosive action;
– in case of intense precipitations, an important fraction of rain water flows above the aerial portion of the vegetation, also when the plants are seasonally dried up;
– the vegetation reduces the speed of water flow at soil level

Effects of roots system within the soil

As well known in the specialized literature (Gray and Sotir, 1996), the roots system in the soil generally favours an increase of shear resistance within the rooted layer; this fact actually depends on two different processes:

1. the mechanical reinforcement of the roots themselves;
2. the ability to the entire grassy system to affect, also in significant way, the hydrologic balance of the involved area, thanks to the ability of the aerial apparatus to deflect part of the rainfall, and to the property of the entire plant that absorbs water from the ground and transfers it to the atmosphere through transpiration.

The interaction - both mechanical and hydraulic - between plant and soil becomes of central importance as the installation of a strong vegetation layer has the twofold goal of primarily protecting soil from the erosion and, secondly, to reduce water infiltration into the ground.

Beside its importance, the subject is obviously complex as several phenomena are involved and their study requires specific skills in various fields like agronomy, soil physics and hydraulics. From a numerical-analytical point of view, the mass balance equations must be respected, taking into consideration the phenomena of soil evaporation, plant transpiration, water infiltration into the soil and water streaming along the slope.

It is worthwhile here recalling only some base concepts of the root/soil interaction mechanisms: on one side plant roots directly increase the shear resistance of soil due to mechanical interaction, acting like thin anchorages of high tensile strength that develop in the soil (Waldron, 1977); on the other side they guarantee, indirectly, a significant contribution to the resistance associated to phenomena of hydro-mechanical nature.

Mechanical effects of roots installation

From a purely mechanic point of view, the direct increase of shear resistance that may be ascribed to the presence of roots can be interpreted using the Waldron approach (1977), proposed on the base of several experimental results of direct cutting tests of rooted soil samples. According to such approach, the “reinforcement” contribution offered by roots can be interpreted in first appraisal as additional “pseudo-cohesion” that increases the shear resistance of the soil.

In the years '70, Wu (1976) and Waldron (1977) proposed a simple theoretical reference model assuming that the rooted soil behaves like a composite material in which linear fibers (roots) of high tensile strength are surrounded by a multiphase material characterized by lower tensile strength.

The reference mechanical scheme for the single root is represented in Fig. 1 where the root is perpendicular to the cutting plane, in undeformed initial conditions.

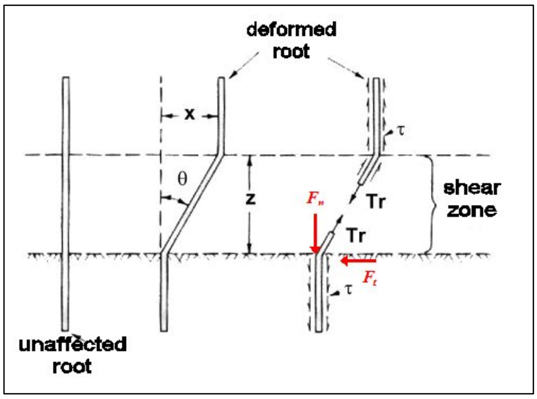

Figure 1 Simplified model of soil reinforcement for the single root growing in perpendicular direction with respect to the cutting plane(adapted from Gray & Leiser, 1989)

The single root, sliding along a potential breaking surface that delimits a lump of unstable soil, undergoes an elastic deformation in the tract of thickness z.

The deformed configuration of the fiber is described as function of the angular distortion θ and of the displacement in the direction of the cutting plane.

Assuming a sufficient insertion depth to prevent the root to slip off the stable land, the strain induced in the fiber yields accumulation of tensile stresses (up to the maximum resistance of the root) unevenly distributed in the internal sections of the root, along a section extending much beyond the tract of thickness z.

Close to the root, the soil shows an increase of shear strength, $\Delta\tau_{rad}$. Such increase is directly proportional to the average value of tensile strength T_R of the roots, to the rooting ratio, as well as to friction angle of the soil ϕ'.

In the case of the simplified model represented in Fig. 1, setting the equilibrium conditions in global terms at the sliding surface, the increase of shear strength due to the roots is expressed by:

$$\Delta\tau_{rad} = \frac{A_R}{A} T_R \left(\sin\theta + \cos\theta \tan\phi'\right)$$

where T_R is the tensile strength of the single root, while the term A_R/A expresses the rooting rate between the total area occupied by the roots, A_R, and the area of the reference soil section A.

The rooting rate is function of the adopted plant specie, and typically decreases with the depth.

The extension of the model proposed for the single root to the entire root system brought several Authors to propose solving equations for the evaluation of the increase in shear strength $\Delta\tau_{rad}$ ascribable to the entire system.

In particular, based on results of experimental tests, several semi-empirical formulas have been proposed, among which the Waldron equation (1977) is to be mentioned, resulting from experimental studies of the years '70:

$$\Delta\tau_{rad} = 1.15 \cdot T_R \frac{A_R}{A} \qquad [2]$$

and the equation of Bonfanti and Bischetti (2001):

$$\Delta\tau_{rad} = 1.15 \frac{A_R}{A} \cdot \left\{ \int_{D_{\min}}^{D_{\max}} T_R(D) \cdot F_d(D)\, dD \right\} \qquad [3]$$

where $D_{\max}$ and $D_{\min}$ express respectively the maximum and the minimum diameter of the roots of a given specie, and the distribution function of roots diameters $F_d(D)$ may be defined through the known probability density functions available in literature (for example, normal, triangular or log-normal).

An extensive experimental investigation was carried on by the Department of Agrarian Engineering of "Università degli Studi di Milano" (Bischetti *et al.*, 2009), aimed at the evaluation of roots tensile strength of the 30 perennial grassy species currently used by Prati Armati srl, mainly belonging to the botanical families of Graminae and Leguminosae.

As an example, the trend of roots tensile strength $T_R(D)$ versus diameter is shown in Fig. 2. The experimental curves are well fitted by exponential functions, whose parameters depend on the grassy species.

Once the increase in shear strength due to the roots system ($\Delta\tau_{rad}$) has been determined, with reference to the scheme of infinite slope it is possible to solve the equation expressing the safety factor (SF) and to quantify the

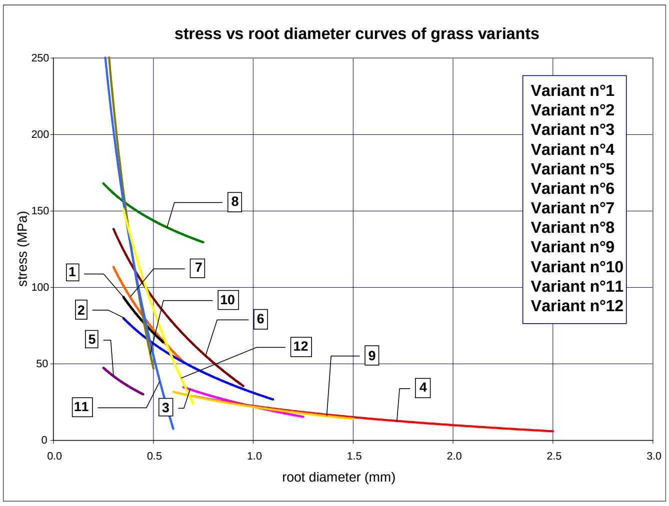

Figure 2 Experimental results of tensile tests on some grassy species (Department of Agrarian Engineering of "Università degli Studi di Milano", 2009)

stabilizing contribution given by roots to the more superficial soil layers, that is:

$$SF = \frac{\tau_f(z) + \Delta\tau_{rad}(z)}{\gamma \cdot z \cos\alpha \sin\alpha} =$$

$$= \frac{c' + \left(\gamma - \frac{D_w}{z}\gamma_w\right) z \cos^2\alpha \tan\phi' + \Delta\tau_{rad}(z)}{\gamma\, z \cos\alpha \sin\alpha} \qquad [4]$$

being:

c' and ϕ': the parameters of soil resistance;

γ and γ_w: respectively the unit weight of soil and the unit weight of water;

α: the slope angle;

z: the depth of the potential sliding surface from the ground level;

$\tau_f(z)$: the soil shear strength along the potential sliding surface;

D_w: the depth of the sliding surface with respect to the free groundwater surface.

It should be finally noted that, independently from the selected equation [2] or [3] the most precautionary state to consider in evaluating the increase of shear strength $\Delta\tau_{rad}$ is not necessarily the upper limit of the single root tensile strength, but could rather be the last limit for root slip off. Comparing the two considered limits it is possible to point out the most precautionary one to be used in equation [4] for the evaluation of the safety factor of the rooted slope.

As an example, a reference case study shows the amount of increase of soil shear resistance due to the mechanical effect of roots implanting. Using a calculation algorithm developed in *VISUAL BASIC - EXCEL* (Rettori *et al.*, 2010), a simple stability analysis has been carried out for the scheme of infinite slope.

In particular the considered slope has an average inclination of 25° and delimits a dump area of compacted and slightly cemented sand (ϕ' = 32°, c' = 4 kPa).

The underground water surface lays at 1 m depth from the ground plane. Assuming that the root systems belong to a mixture of deep roots grassy plants with average root diameter of 0,8 mm, and capable to reach a root depth of 3 m, the increase of shear strength $\Delta\tau_{rad}$ has been calculated with equation [3].

Fig. 3a shows the trend of such increase while Fig. 3b represents the safety factors SF calculated by equation [4], both for rooted and non rooted soil, plotted against the depth z from the ground plane. Note that $\Delta\tau_{rad}$ decreases with the depth, obviously in the same way as the safety factor for the rooted soil.

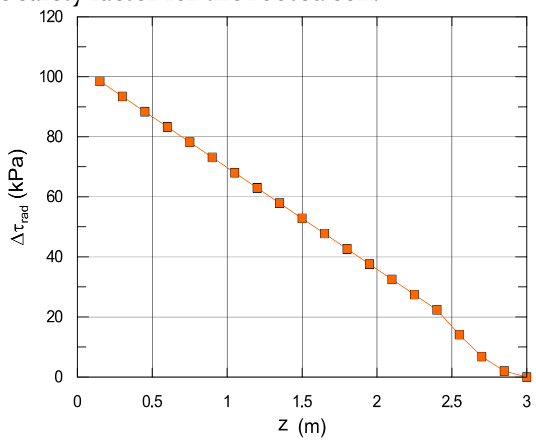

Figure 3a Increase in shear resistance $\Delta\tau_{rad}$ due to the roots, plotted against depth

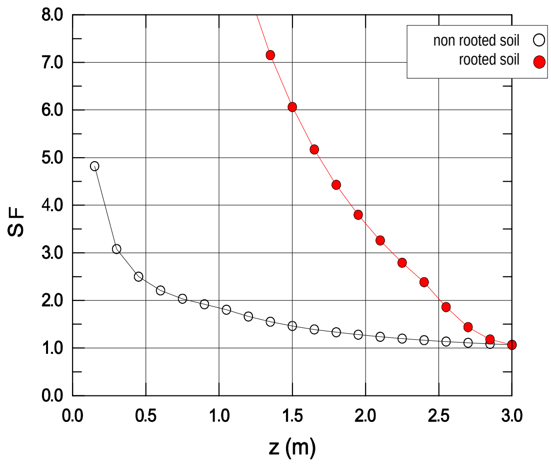

Figure 3b Safety factor SF of non rooted (empty circles) compared to rooted soil (red filled circles)

It must be also underlined that, although SF may be even tripled by the presence of roots, in any case the initial conditions must start from SF>1 (stable slope).

Hydraulic effects of the plant system

Besides the mechanical effect described in the previous paragraph, the whole plant contributes to increase the soil shear resistance as the combined action of the deep roots system and the strong aboveground vegetation results in a significant reduction of soil water content.

In order to understand, even from the pure phenomenological point of view, the mechanical and hydraulic interaction schemes between plant and soil, it is necessary to analyze the equation of mass balance, accounting for phenomena of plants evapo-transpiration, water infiltration into the soil, water streaming along the slope. A simplified representation of the phenomena is reported in Fig. 4.

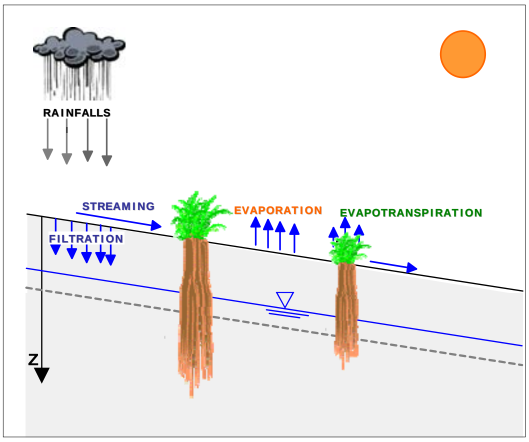

Figure 4 Schematic representation of principal contributions to water balance

The water balance may be described by the following expression:

$$\sum_{\Delta t}(P-P_I)=\sum_{\Delta t}E+\sum_{\Delta t}T+\sum_{\Delta t}I+\sum_{\Delta t}R \quad [5]$$

where:

Δt: time reference period;

P: total rainfall, represented by a stochastic variable and locally measured by weather stations;

P_I : rain received by the aerial portion of the vegetation;

E : evaporation from the surface of soil layer;

T : transpiration;

I : water infiltration in the most superficial soil layer;

R: amount of water involved in streaming phenomena (*run-off*) along the slope.

Concerning P_I , one of most known expressions found in literature (Von Hoyningen-Hune, 1983; Braden, 1985) for vegetation of agricultural type is in the form:

$$P_I = a \cdot LAI\left(1-\frac{1}{1+\dfrac{b\cdot P}{a\cdot LAI}}\right)$$

where:

LAI: Leaf Area Index;

a: empirical coefficient, depending on the type of cultivation;

b: soil fraction covered by vegetation, also function of LAI index and of sunlight extinction coefficient k_{gr}.

For a quantitative assessment of E , T parameters, the *crop evapo-transpiration* method may be used (Feddes, 1987; Allen *et al.*, 1998):

$$ET_c = (K_{cb}+K_e)ET_0$$

where K coefficients respectively quantify the transpiration capacity of the specie under investigation along it's growth period, and the soil evaporation capacity as function of last rain event and leaves cover.

ET_o represents the daily average reference evapotranspiration (Hargreaves & Samani, 1985).

In order to quantitatively assess the effects of roots planting - taking into consideration all the mentioned phenomena - and to estimate the surface stability of a grass-covered slope, it is necessary to define the distribution of water content and degree of saturation as function of depth, and therefore to realistically simulate the infiltration phenomenon (*I*). To this aim, in the hypothesis that the rooted soil be in condition of partial saturation, the well known Richards equation (1931) may be effectively adopted:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial t}\left[D(\theta)\frac{\partial \theta}{\partial z} \right] - \frac{\partial K(\theta)}{\partial z} \qquad [6]$$

where θ is the water content soil unit volume, $K(\theta)$ its hydraulic conductivity, and the diffusivity coefficient $D(\theta)$ is defined by:

$$D(\theta) = K(\theta)\frac{\partial h}{\partial \theta}$$

with h = hydraulic load.

The numerical solution of Richards equation, while respecting the water balance equation, allows to calculate the soil water content $\theta(z, t)$ vs time along all the rooted profile. When $\theta(z, t)$ is known, it is possible to compute the suction profile $s(z)$ making use of water retention graphs (*SWCC*) available in specialized literature (eg: Fredlund & Xing, 1994; Van Genuchten, 1980).

Finally, assuming a breaking criterion that takes into account the partial saturation (e.g.: Fredlund *et al.*, 1996; Rassam and Cook, 2002; Vanapalli *et al.*, 1996), the suction profile allows to estimate the soil shear resistance and the equilibrium conditions of the slope synthetically expressed by the safety factor SF.

For example, assuming as breaking criterion for a non-saturated soil the equation proposed by Vanapalli *et al.*, (1996), the shear strength appears directly influenced by θ and s through:

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + s\cdot\left[\tan\phi'\frac{\theta-\theta_r}{\theta_s-\theta_r}\right] \qquad [7]$$

where $(\sigma_n - u_a)$ is the normal pure tension and θ_s, θ_r respectively represent the water content at saturation and the residual one.

With reference to the scheme of infinite slope, the safety factor may be still calculated by equation [4], where the soil strength τ_f is computed through equation [7].

Example of anti-erosion intervention

A typical example of Prati Armati® installation was carried out in a Central Italy site and the results are reported in Fig. 5 and Fig. 6.

In particular in December 2004, in correspondence of a slope of remarkable height and steepness (40°÷ 80°) consisting of pyroclastites and strongly altered basaltic outcrops, a surface sliding took place causing the obstruction of the underlying road “SP111 della Badia” (see Fig. 5a).

Figure 5a Orvieto (Terni, central Italy), road “SP111 della Badia” Situation of the slope in December 2004, before intervention

Only few months after the intervention, the implanted grassy species completely renaturized the surface layer of the slope, despite the lithologic and morphologic conditions unfavorable to root taking. The strong vegetation layer prevents water infiltration and efficiently blocks the erosion process (Fig. 5b).

Figure 5b Same slope after renaturation intervention (May 2006)

The last statement results particularly evident from Fig. 6, showing the trench drains at the foot of the slope before and after intervention: their clean state enhances the effectiveness of the technology in minimizing the maintenance needs of the hydraulic systems works.

Conclusions

Erosion phenomena and surface instability events of slopes may be effectively contrasted by vegetal blankets with deep root systems. Such technology, simply consisting on seeding perennial grasses, appears effective, quick to realize and does not require any maintenance.

It is recognized that an efficient protection (deep roots and strong aboveground vegetation) may affect mechanical and hydraulic conditions of the slope, which in turn would influence the equilibrium conditions of potentially sliding surface portions of soil.

a) clogged drains b) clean drains

Figure 6 Same slope of Fig. 5 showing (a) trench drains before treatment (September 2005) and (b) 8 months later (May 2006)

The effects of root installation are first recognizable as mechanical reinforcement due to the same roots; moreover, the grass system affects, even meaningfully, the hydrologic balance of the involved area, thanks to the ability of the aerial plant system to shield part of rainfalls and to transfer to the atmosphere by transpiration the water absorbed from the ground.

The Authors recently started a study aimed at numerical modeling of hydraulic/mechanical interactions between roots and soil. The expected results, still not available, will allow the quantitative evaluation of shear resistance improvement due to the installation, and the assessment of safety and equilibrium conditions limited to shallow instability phenomena.

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