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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Role of vegetation on slope stability under transient unsaturated conditions

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Abstract

We examine the role of vegetation on the stability of shallow soils under unsaturated transient regime. Two main positive effects of the vegetation on slope stability are discussed: i) a geo-mechanical effect, i.e., the reinforcement of soil by plant roots; ii) a soil-hydrological effect, i.e., the soil suction regime affected by root water uptake. The root distribution is assessed by an eco-hydrological model, which predicts the root density as function of local climatic conditions in growing season and soil hydrological properties. The predicted root distribution is employed for assessing the vertical variability of both the apparent soil cohesion provided by roots and the root water uptake. A one-dimensional model of vertical soil water dynamics is employed for simulating soil suction regime, assumed representative of well-drained soils on steep forested plane slopes. The geo-mechanical and the soil-hydrological effects on slope stability are examined with an infinite slope stability model, generalized for unsaturated conditions. We show that in the case of a loamy-sand soil under a Mediterranean climatic regime, the geo-mechanical effect tends to be more relevant than the soil-hydrological effect during the rainy season, within depths up to twice the average root depth.

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1. Introduction

Many regions of the world are exposed to destructive fast flows initiated by shallow landslides occurring on steep slopes after extreme rainfall events. These slopes often consist of well-drained and poorly cohesive colluvial soils [e.g., 1] or pyroclastic deposits [e.g., 2] covered by dense forest, with a slope angle larger that the internal soil friction angle. The stability conditions of these slopes depend on the mechanical reinforcement provided by the plant roots to the soil and on the soil suction regime in the unsaturated soils, which in turn is also influenced by root water uptake. Assessing stability enhancement due to vegetation is an important aspect for a reliable assessment of the spatial and temporal distribution of these shallow landslide hazards [e.g., 3], as well as for a proper evaluation of the best forest management strategies for hazard mitigation.

In the last decades several studies demonstrated that hillslope morphology and processes are highly influenced by vegetation distribution [e.g., 4]. Vegetation has generally a positive impact on the stability of soils on sloping surfaces within the vadose zone, according to two main effects [e.g., 5]:

- a geo-mechanical effect, related to the reinforcement provided by the root network which explore the soil in the vadose zone in order to maximize the efficiency in water uptake and guarantee the stability of the above ground canopy;
- a soil-hydrological effect, by increasing the frequency of high suction pressure head values as result of the root water uptake.

These two effects are also very much interrelated. On the one hand, root distribution is influenced by the climatic regime and soil-hydrological properties, particularly in areas where plant-growth occurs in water-limited conditions. On the other hand, mechanical properties of the root–soil system are affected by the actual soil strength, the single root strength, the interface strength between soil and roots [e.g., 6] and the root spatial structure [e.g., 7].

This study discusses the relative role of these two effects with a numerical experiment examining the temporal variability of their relative weight on the stability of a slope covered by a homogenous loamy-sand soil, with a meteorological forcing typical of a Mediterranean climate in Southern Italy.

2. Modelling framework

2.1. Infinite slope stability model

Slope-stability analyses are commonly performed using limit-equilibrium methods, which express the stability by an indicator called "factor of safety" (F), defined as the ratio of the available shear strength to the shear stress expected along the failure surface. In case of shallow landslides, the failure plane can be assumed parallel to the surface slope and all force components not resolvable on the plane parallel to the surface slope can be neglected. Under such conditions, F can be simply estimated by the infinite slope stability model. In this study we refer to the infinite slope stability model generalized for unsaturated conditions in the soil, following Lu and Godt [8].

If we consider air perfectly drained at constant atmospheric pressure in soil pores, the factor of safety of a vegetated slope at a generic depth z measured along the vertical direction (taken positive downward with z=0 at the surface) is estimated as follows:

$$F = \frac{c' + c_r + \left(\gamma z \cos^2 \beta + \gamma_w h S_e\right) \tan \varphi'}{\gamma z \sin \beta \cos \beta} \qquad (1)$$

where:
- c' is the soil effective cohesion;
- c_r is the apparent soil cohesion due to the reinforcement provided by plant roots;
- φ' is the effective soil friction angle;
- β is the slope angle;
- h is the suction head;
- S_e is the effective saturation;
- γ is the depth-average specific weight of the soil column above z, including additional weight, such as that due to above ground vegetation;
- γ_w is the water specific weight.
  S_e can be estimated as a function of the pressure head h, as follows:

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \tag{2}$$

where $\theta(h)$ ($cm^3 cm^{-3}$) is the soil water content at suction head h, according to the soil water content retention function, while θ_r is the residual soil water content and θ_s is the soil water content at saturation.

Parameter γ is computed as follows:

$$\gamma = \gamma_s + \frac{1}{z}\left[W_v + \gamma_w \int_0^z \theta ds \right] \tag{3}$$

where γ_s is the specific weight of the dry soil and W_v is the additional weight per unit surface due to above ground vegetation, which is generally neglected.

It is interesting to observe that Eq. (1) can be obtained as the sum of four components, as follows:

$$F = F_\varphi + F_c + F_w + F_r \tag{4}$$

F_φ is the stability contribution due to the internal friction related to mean net stress perpendicular to the failure plane:

$$F_\varphi = \frac{\tan \varphi'}{\tan \beta} \tag{5a}$$

F_c is the stability contribution provided by the soil cohesion c':

$$F_c = \frac{2c'}{\gamma z sen(2\beta)} \tag{5b}$$

F_w is the stability contribution to available shear strength due to suction stress:

$$F_w = \frac{2h\gamma_w \tan \varphi' S_e}{\gamma z sen(2\beta)} \tag{5c}$$

F_r is the stability contribution due to the soil cohesion c_r generated by the plant root reinforcement:

$$F_r = \frac{2c_r}{\gamma z sen(2\beta)} \tag{5d}$$

Vegetation affects slope stability by influencing both terms F_w (soil hydrological effect) and F_r (soil geo-mechanical effect).

2.2. Modelling soil reinforcement by plant roots

For the stability analysis of vegetated slopes, we have to quantify the apparent soil cohesion provided by plant roots. Several models have been suggested for assessing these apparent soil cohesion due to roots, under different assumptions concerning root distribution and tensile strength.

The most popular model is the one suggested by Wu et al. [9], which is based on the following assumption: all roots are aligned perpendicular to the shear plane; full tensile strength of all roots is mobilized at the time the soil fails; all roots are well anchored and do not simply pull out of the soil when tensioned.

Recently, innovative models have been proposed, known in literature as Fiber or Root Bundle Models, however these models require a larger number of data in order to be implemented [6, 10].

In this paper, for sake of simplicity, we refer to a modified version of the traditional model suggested by Wu et al. [8, 10]. According to this model, the root cohesion (c_r) is

$$c_r(z) = k' \cdot k'' \cdot T_r \cdot RAR(z) \tag{6}$$

In Eq. (6), $RAR(z)$ is the root area ratio, i.e., the ratio of total cross-sectional area of the roots at a given depth z and the extent of the area explored by the root system in a vertical plane (assuming root distribution having a rotational symmetry); T_r is the mean tensile strength of the roots; parameter k', usually considered equal to 1.2, is a correction factor used to account for the fact that roots are not oriented perpendicular to the sliding surface; parameter k'' is a bias correction factor and it is assumed equal to 0.4.

$RAR(z)$ is defined by the following exponential function, derived by Preti et al. [11] by means of an eco-hydrological model :

$$RAR(z) = RAR_0 e^{-z/b} \tag{7}$$

Parameter b accounts for both local climatic conditions and soil water retention properties, being defined as follows:

$$b = \frac{\alpha}{\left(\theta_{fc} - \theta_w\right)\left(1 - \lambda\alpha / T_{GS}\right)} \tag{8}$$

In Eq. (3), parameters α, λ and T_{GS} characterizes the local climatic conditions in the growing season. Rainfall is modeled as a marked point process, i.e., as a sequence of instantaneous rainfall pulses with rate λ [T^{-1}] and depths drawn from an exponential cumulative probability distribution, with a mean value equal to α. T_{GS} is the average potential transpiration for the growing season. The remaining parameters θ_{fc} and

θ_w are the soil water content at field capacity and wilting point.

2.3. Model of soil water dynamics

We employed the SWAP (Soil, Water, Atmosphere and Plant) model for simulating soil water flow under unsaturated conditions [12]. SWAP simulates the temporal variability of the suction head (h) in the vadose zone by a numerical integration of the Richards equation.

Using the suction head (h) as state variable, the Richards equation can be written as follows:

$$C\left(h\right)\frac{\partial h\left(z,t\right)}{\partial t} \;=\; \frac{\partial}{\partial z}\left\{K\left(h\right)\left[\frac{\partial h\left(z,t\right)}{\partial z}-1\right]\right\}-S\left(h\right) \tag{9}$$

where t is the time; z is the depth from the soil surface (taken positive downward); the parameter $C(h)=d\theta/dh$ is the differential soil water capacity, which can be obtained from the soil water retention function, $\theta(h)$; $K(h)$ is the hydraulic conductivity function. After having specified the appropriate initial and boundary conditions, the SWAP model solves Eq. (9) numerically using a finite-difference approach.

The soil water retention and soil hydraulic conductivity functions are herein defined according to the van-Genuchten/Mualem analytical relationships:

$$\theta \;=\; \theta_r +\left(\theta_0 - \theta_r\right)\left[1+\left(\alpha_{VG}\cdot h\right)^{n_{VG}}\right]^{-m_{VG}} \tag{10}$$

$$K\left(\theta\right)=K_s S_e^{\lambda_{VG}}\left[1-\left(1-S_e^{1/m_{VG}}\right)^{m_{VG}}\right]^2 \tag{11}$$

where K_s is the saturated hydraulic conductivity and α_{VG} [L^{-1}], n_{VG} (-), m_{VG}(-) and λ_{VG}(-) are empirical scale and shape parameters. In this work we assume λ_{VG} =0.5 and m_{VG} =1-1/ n_{VG}. Parameter θ_0, i.e., the value of the soil water content provided by the water retention curve for h=0 according to Eq. (10), is assumed equal to θ_s.

The sink term, $S(h)$, is introduced to simulate the water extraction from the roots as a function of suction head, h:

$$S\left(h\right) \;=\; \chi\left(z\right)\xi\left(h\right)T_p \tag{12}$$

In Eq. (12), $\chi(z)$ [L^{-1}] is defined by a normalized root density distribution function, which is here derived from Eq. (7) defining the root area ratio distribution $RAR(z)$:

$$\chi\left(z\right)=\frac{RAR\left(z\right)}{\displaystyle\int_0^\infty RAR\left(s\right)ds}=\frac{e^{-z/b}}{b} \tag{13}$$

T_p [LT^{-1}] is the maximum transpiration rate which is reached under condition of no stress for the vegetation, whereas $\xi(h)$ ($0\leq\xi\leq1$) is a factor describing the reduction of the actual transpiration with respect to T_p as function of the suction head. Under conditions of no stress, the sink term represents the

maximum uptake rate, $S = \chi \cdot T_p$. In this study, the function parameter $\xi(h)$ is simplified as follows:

$$\xi(h) = \begin{cases} 0 & 0 \leq h < h_1 \\ 1 & h_1 \leq h \leq h_2 \\ 1 - \dfrac{h - h_2}{h_3 - h_2} & h_2 < h \leq h_3 \\ 0 & h_3 < h < +\infty \end{cases} \qquad (14)$$

The condition $0 \leq h < h_1$ corresponds to the air deficiency, while $h_1 \leq h \leq h_2$ accounts for a conditions of no water stress and $h_2 < h \leq h_3$ describes water stress conditions. The value h_3 corresponds to the permanent wilting point.

3. Numerical experiment

3.1. Soil column parameterization

We consider a homogeneous soil column of 200 cm, which hydraulic properties have been assumed equal to those of a loamy-sand soil samples in Southern Italy reported by Romano et al. [13].

The parameters of the soil hydraulic functions (Eqs. 2a,b) are listed in Table 1. Soil field capacity (θ_{fc}) is assumed equal to the value estimated by Romano et al. [13] for the same soil by means of a simulated drainage experiment.

Table 1. Soil hydraulic properties

Soil Texture	θ_r	θ_s	α_{VG}	n_{VG}	K_s	h_1	h_2	h_3	θ_w	θ_{fc}
	(-)	(-)	(cm^{-1})	(-)	$(cm\,day^{-1})$	(cm)	(cm)	(cm)	(-)	(-)
Loamy-sand	0.036	0.447	0.025	1.391	86.8	1.0	300	16,000	0.105	0.246

3.2. Reference climatic scenario

The reference climatic scenario is defined according to the data of a meteorological station located in Campania Region, characterized by a Mediterranean climate of sub-humid type according to the Thornthwaite classification. The climatic parameters required for assessing the reference root distribution have been computed considering a growing season from March to October, excluding the months of July and August, which have been considered as part of the dormant dry season typical of the Mediterranean regions.

Table 2. Reference climatic parameters for the growing season

T_{GS}	λ	α
(mm/day)	(events/day)	(mm/event)
2.98	0.20	12.57

3.3. Root distribution and soil cohesion provided by roots

Table 3 lists the parameters employed for estimating root distribution and root cohesion. RAR_0 and T_r correspond to typical values of a deciduous forest of the Apennine Range of Campania Region (e.g., *Castanea sativa* Mill.). The mean root depth b is instead computed according to Eq. (8), exploiting the parameters listed in Table 1 and 2.

Table 3. Parameters for assessing root distribution and soil cohesion provided by roots

RAR_0	T_r (kPa)	b (cm)
0.0025	36,000	50.2

3.4. Soil strength properties

Values of the geo-mechanical soil properties employed within the numerical experiment are listed in Table 4. These are values representative of a loamy-sand soil, with negligible effective cohesion, as it can be observed in many slopes of the Apennine limestone range in Campania Region.

Table 4. Soil strength properties

φ'	c' (kPa)	γ_s (kN/m^3)
30°	0	14.6

3.5. Initial and boundary conditions for the soil water dynamics model

A Neumann boundary condition is imposed at soil surface, by assuming the downward flux at the soil surface equal to the rainfall intensity, which is always smaller than the saturated hydraulic conductivity and thus ponding conditions cannot occur. Evaporation fluxes from the soil column are assumed negligible, as it would be in case the ground surface is fully covered by canopy. However, canopy interception loss is not explicitly simulated, being irrelevant for the aim of the present study. Rainfall and potential transpiration have been taken from one year of daily data recorded at a meteorological station located Campania Region, as depicted in Fig. 1. We selected year 2006, characterized by a summer season with more rain showers than usually registered in Campania.

The lower boundary condition is also of Neumann type, being specified by free drainage as it can be assumed for deep and relatively homogenous soils.

The effect of the initial conditions has been removed by performing the simulation for two consecutive years with the same top boundary conditions, while examining the results of the second year only.
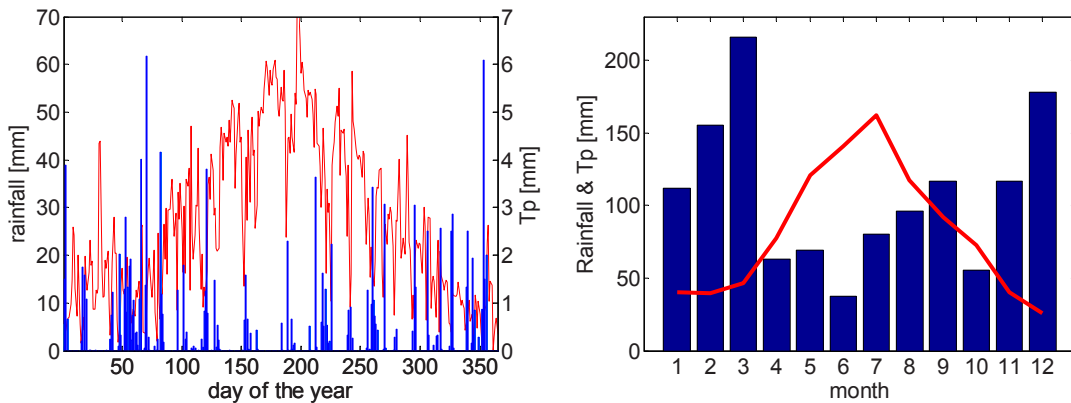
Fig. 1. Left: daily rainfall and potential transpiration series employed within the numerical experiment. Right: monthly rainfall and potential transpiration. "Day of the year" indicates the day number starting from the 1st of January of the simulated year.

4. Results

The seasonality of the Mediterranean climates is clearly reflected by the soil water potential regime and thus by F_w time variability. Fig.2, left side graph, shows the temporal evolution of F_w within the depth interval from 20 cm up to 100 cm. During the rainy season, F_w reaches values above 1 only at depths smaller than 80 cm, provided that the transpiration rate is limited to relatively small potential values during the short inter-storm time intervals. The transpiration effects on the soil suction profile become instead relevant in the growing and summer dry season, when F_w is consistently larger than 1 at greater depths.

Differently from F_w, F_r presents a limited variability with time. The time variation of F_r is only due to changes of the average specific soil weight γ associated with the variability of the average soil water content, according to Eq. 3. Fig. 2, right side graph, shows an example of mean value of depth distribution of F_r, together with the corresponding 10th and 90th percentiles. F_r reaches values greater than 1 for depths smaller than 80 cm.

We assess the relative weight of F_w with respect to F_r by computing the following index, which is independent from the slop angle:

$$f_w = \frac{F_w}{F_w + F_r}100 = \frac{h\gamma_w \tan\varphi' S_e}{h\gamma_w \tan\varphi' S_e + c_r} \tag{15}$$

As shown in Fig. 3, during the wet period f_w generally assumes values smaller than 50% for depths smaller than 100 cm. In other words, during the wet periods the geo-mechanical effect (F_r) tends to be greater than the soil hydrological effect (F_w) within depths smaller than twice the mean root depth (b=50.2 cm). During the growing and dry summer seasons F_w is far the most relevant effect even in the case of a relatively more rainy summer, as in the examined case study.
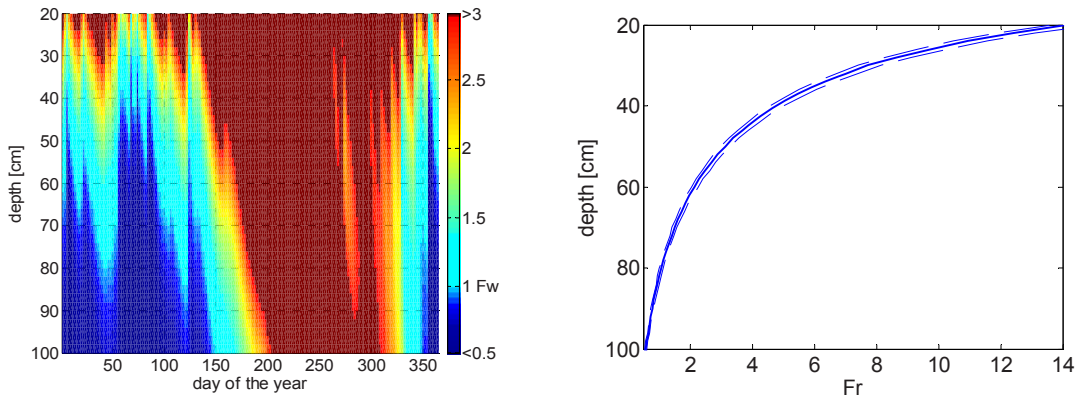
Fig. 2. Left: temporal pattern of F_w along the soil column for depths between 20 and 100 cm for β=35°. Right: mean depth distribution of F_r for β=35°, with corresponding 10th and 90th percentiles.
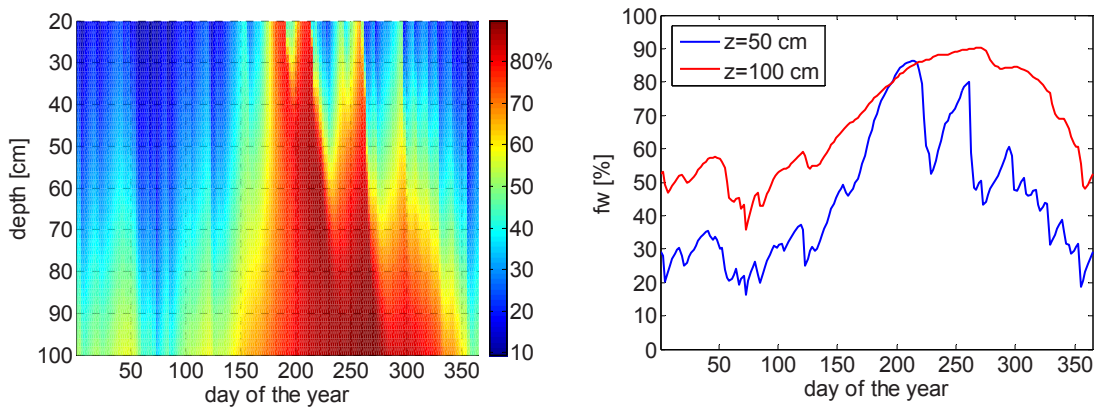

Fig. 3. Left: temporal pattern of f_w along the soil column for depths between 20 and 100 cm. Right: time-series of f_w at depths of 50 cm and 100 cm.

5. Conclusions

Shallow landslides can occur on natural steep slopes (i.e., with slope angle larger than the effective soil friction angle) covered by well-drained colluvial soils or pyroclastic deposits, triggered by infiltrating rainfall, even along failure planes far from saturation conditions [e.g., 8]. On such slopes, vegetation has a relevant role in mitigating shallow landslide hazards, essentially by two dominant mechanisms: i) root water uptake, which contributes to enhance the stability by increasing the frictional resistance associated with the soil suction; ii) soil reinforcement by the root structure, which enhances the stability by providing an added apparent cohesion to the soil. These two mechanisms are very much interrelated in water controlled eco-systems, such as Mediterranean areas, where water availability is limited during the growing season and plants develop their root structure in order to optimize the uptake of the water available in the soil.

With the aim to provide some hints about the relative weight of these two mechanisms, we simulated the soil water dynamics within a homogeneous loamy-sand soil for a period of one year, assuming climatic conditions typical of a Mediterranean area. The modeling framework is too simplified for being

employed to assess the actual stability of natural slopes, which are affected by other factors herein not represented, such as the vertical heterogeneity of the soil properties, the lateral soil water flows (influenced by the terrain morphology) and soil layers orientation. Moreover, simulations have been performed with meteorological forcing applied at relatively coarse time resolution (daily), while it is well known that the soil suction regime at shallow depths is highly influenced by the rainfall variability at small time resolutions and very often shallow landslides are triggered by rainfall bursts at time-scale of the order of a few tens of minutes.

The results of the examined case study suggest that during the wet season, the effect of the soil suction state on slope stability is smaller than that attributable to the mechanical reinforcement provided by the root structure, within soil depths explored by the plant roots. Instead, during the growing and dry summer seasons, the soil suction state is far more relevant than the mechanical reinforcement. Reminding that most of the shallow landslides in Mediterranean regions are associated with intense convective rainstorms occurring at small time and spatial scales during the growing and dry seasons, we can argue that plant water uptake has also a fundamental role in establishing pre-event soil states favorable for slope stability.

Acknowledgements

References

[1] de Campos TMP, Andrade MHN, Vargas EA. *Unsaturated colluvium over rock slide in a forested site in Rio de Janeiro, Brazil.* Proc. 6th Int. Symp. on Landslides, Christchurch New Zealand, Balkema, Rotterdam, Netherlands; 1991, p. 1357-1364.

[2] Andriola P, Chirico GB, De Falco M, De Crescenzo P, Santo A. A comparison between physically-based models and a semiquantitative methodology for assessing suceptibility to flowslides triggering in pyroclastic deposits of southern Italy. *Geografia Fisica e Dinamica Quaternaria* 2009;**32**:213-226.

[3] Roering JJ, Schmidt KM, Stock JD, Dietrich WE, Montgomery DR. Shallow landsliding, root reinforcement, and the spatial distribution of trees in the Oregon Coast Range. *Canadian Geotechnical Journal* 2003;**40**:237-253.

[4] Marston RA. Geomorphology and vegetation on hillslopes: Interactions, dependencies, and feedback loops. *Geomorphology* 2009;**116**:206-217.

[5] Pollen N. Temporal and spatial variability in root reinforcement of streambanks: accounting for soil shear strength and moisture. *Catena* 2007;**69**:197–205.

[6] Waldron L, Dakessian S. Soil reinforcement by roots: calculation of increased soil shear resistance from root properties. *Soil Sci* 1981;**132**:427–435.

[7] Schwarz M, Preti F, Giadrossich F, Lehmann P, Or D. Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy). *Ecol Eng* 2010;**36**:285-291.

[8] Lu N, Godt J. Infinite slope stability under steady unsaturated seepage conditions. *Water Resour Res* 2008;**44**:W11404.

[9] Wu TH, Mckinnell WP, Swanston DN. Strength of tree roots and landslides on Prince Of Wales Island, Alaska. *Can Geotech J* 1979;**16**:19-33.

[10] Preti F, Giadrossich F. Root reinforcement and slope bioengineering stabilization by Spanish Broom (Spartium junceum L.), *Hydrol Earth Syst Sci* 2009;**13**:1713-1726.

[11] Preti F, Dani A, Laio F. Root profile assessment by means of hydrological, pedological and above-ground vegetation information for bio-engineering purposes. *Ecol Eng* 2010;**36**:305-316.

[12] van Dam JC, Groenendijk P, Hendriks RFA, Kroes JG. Advances of modeling water flow in variably saturated soils with SWAP. *Vadose Zone J* 2008;**7**:640-653.

[13] Romano N, Palladino M, Chirico GB. Parameterization of a bucket model for soil-vegetation-atmosphere modeling under seasonal climatic regimes. *Hydrol. Earth Syst Sci* 2011;**15**:3877-3893.