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Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy)

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ABSTRACT

Vegetation significantly affects hillslope hydrological and mechanical properties related to shallow landslide triggering. In view of the complexity of soil plant hydrological interactions, the quantification of root mechanical reinforcement remains a challenge. Herein we present a back analysis of mechanical stability criteria related to a well-characterized vegetated shallow landslide in Italy, focusing on the quantification of lateral and basal root reinforcement. Lateral root reinforcement is included in slope stability estimates by adding a stabilizing force proportional to the scarp surface and root distribution. This stabilizing force is added to the force balance equation for the infinite slope model for different landslide shapes and dimensions. To quantify root reinforcement, we use the Wu model and the fiber bundle model (WM and FBM, respectively). Implementation of the latter model allows the quantification of the stress–strain behaviour of a bundle of roots for different root distributions and mechanical properties. Results of these models are compared highlighting key differences between the two approaches. Calculations using the FBM can explain the overestimation of lateral root reinforcement using WM and the commonly observed overestimation in the factor of safety. The model also quantifies the displacement-dependent behaviour of root reinforcement on vegetated slopes. Lateral root reinforcement can strongly influence the stability of slopes up to a certain area (1000–2000 m^2). The magnitude of this stabilizing effect depends on parameters such as inclination, soil mechanical properties, and root distribution.

1. Introduction

Understanding and quantifying the mechanical effects of vegetation on steep slopes remains an unresolved problem. Modelling approaches span a wide range of spatial scales, from modelling of a single root to modelling the stability of an entire vegetated slope. The combination of different spatial and temporal scales and the various processes and elements present in a vegetated system make quantitative description complex and sometimes contradictory. A growing number of models are employed for quantifying root reinforcement; however, direct comparisons between model predictions and data remain sketchy. Recently, the application of the fiber bundle model (FBM) for the estimation of root reinforcement proposed by Pollen and Simon (2005) has emerged as a useful representation of mechanical and geometrical characteristics of plant root systems. The model has previously been used extensively in engineering and material sciences to study the breakdown of complex heterogeneous materials (Peires, 1926; Kun et al., 2007). In addition to other well-known methods and techniques used to study root reinforcement, like shear, pullout, or centrifuge tests (Anderson et al., 1989; Zhou et al., 1998; Fan and Su, 2008), back analysis offers a useful approach to understand the potential contribution of root reinforcement to mechanical stability of a natural slope. Usually, the effects of roots on slope stability at the slope or catchment scale are implemented in two-dimensional models where lateral effects are neglected and reinforcement is considered only if roots cross a slip surface (Sidle and Wu, 2001; Bathurst et al., 2007). In many instances, the root reinforcement effect is homogenized and added as a uniform cohesion term at the stand scale, neglecting inherent geometrical distribution and local variability. Only a few examples treat lateral effects of roots in three-dimensional models (e.g., Schmidt et al., 2001; Kokutse et al., 2006). Casadei et al. (2003), Casadei and Dietrich (2003) and Dietrich et al. (2008) were the first to introduce the aspect of lateral root reinforcement in slope stability calculation and to discuss the

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Table 1
Comparison of computed values of correction factor k'' for different studies, where c_v is the apparent root cohesion estimated with the Wu model (Wu et al., 1979).

Case study	Author	c'_v (kPa)	Methods used for the verification of c'_v	Verified values of c'_v (kPa)	k''
Salix esigua Sandbar Willow	Pollen (2007)	3	Cumulative displacement–stress curve	1.5	0.5
Grass roots	Pollen et al., 2004	17.5	Direct shear-box tests	6	0.34
P la fanus Occidentals, Eastern Sycamore	Pollen et al., 2004	5.6	Cumulative displacement–stress curve	2.31	0.41
PI at anus Occidentals, Eastern Sycamore	Pollen et al., 2004	5.6	Rip Root model	2.48	0.44
Wood Rods reinforcement	Shewbridge and Sitar, 1989	3.7	Shear tests	1.8	0.49
Reed fibers	Gray and Ohashi (1983)	1.5 [kN]	Laboratory-shear tests	0.6 [kN]	0.40
Copper wires	Gray and Ohashi (1983)	0.72 [kN]	Laboratory-shear tests	0.3 [kN]	0.42

influence of this parameter on the dimension of landslides. In this work we apply a similar concept for a specific case study. The effect of mechanical reinforcement by roots under a forest canopy is often limited to surface soil layers (90% of the roots in the first 50 cm of soil depth) (Schmidt et al., 2001; Roering et al., 2003; Bischetti et al., 2005). Consequently, only lateral roots are considered to contribute to slope stabilization. In this work we report data collected to characterize the triggering mechanisms of a shallow landslide that occurred in Tuscany (Italy) during a rainfall event in November 2000.

Motivated by a back analysis of this event, we discuss more general issues related to slope stability analysis of vegetated hillslopes, particularly the application of two different root reinforcement models and the use of slope stability calculations which take into account the role of lateral root reinforcement (Reneau and Dietrich, 1987; Schwarz and Preti, 2007). In addition, we consider the role of soil moisture on slope stability calculation, either as suction or pore-water pressure at limit equilibrium conditions.

We begin by illustrating the primary conceptual differences between the classical model of Wu et al. (1979) for quantifying root reinforcement and the fiber bundle model (FBM) of Kun et al. (2007).

The model introduced by Wu et al. (1979), in the following text denoted as Wu model (WM), provided a pioneering contribution to the quantitative consideration of the mechanical role of vegetation in slope stability. The model considers the dependency of maximal tensile strength on root diameter (Wu et al., 1979).

$$c_{veg.} = \alpha \frac{\sum_{i=1}^{n} T_i n_i a_i}{A} \tag{1}$$

where T_i is the maximal root tensile strength (MPa) of the diameter class i, n_i is the number of roots in the diameter class, a_i is the cross-section area of the root diameter class (m^2), α is a correction factor which takes in account the inclination of the roots crossing the shear plane or the tension crack (the value varies between 1 and 1.2), and A is the area of soil occupied by the roots (m^2).

Additional studies by Waldron and Dakessian (1981) and others advanced the understanding of the mechanisms for root reinforcement in soils. Incorporating these concepts into simple factor of safety calculations reveal consistent overestimation of the role of root reinforcement of soils based on Wu's model (e.g., Pollen and Simon, 2005; De Baets et al., 2008; Docker and Hubble, 2008; Fan and Su, 2008; Mickowski et al., 2007). A summary of various experimental studies is presented in Table 1 showing the magnitude of the overestimation. A "correction factor" (frequently denoted as k'') emerged from comparison of experimental data with model predictions and the average value of this factor is about 0.4 (Preti, 2006; Preti and Schwarz, 2006). The "correction factor" is calculated as the quotient between the measured data value and value estimated with the model of Wu. This overestimation is attributed primarily to Wu's assumption that all roots break at the same time regardless of their diameters. The introduction of the FBM to quantify root reinforcement (Pollen and Simon, 2005) allows incorporating mechanical contributions as a function of root diameters and improves understanding of how a bundle of roots with varying mechanical properties breaks. The general formulation of the FBM assumes that at a certain strain (ε) fibers of class j with strength threshold $\sigma_{\max_j} < E_j\varepsilon$ are broken (or have a plastic residual strength), while remaining fibers carrya load equal to $E_j\varepsilon$, where E_j is the young's modulus of the fiber class j. The global behaviour of the bundle is calculated as

$$\sigma(\varepsilon) = \sum_{j=1}^{n} E_j \varepsilon \tag{2}$$

In this study we will also summarize the technique used to consider root reinforcement at the slope scale. With reference to a case study, we introduce a potential approach for vegetated slope stability estimation, considering lateral root reinforcement and balancing the burden of detailed and spatially resolved calculations and the relatively large (and practical) scale of the required information.

2. Materials and methods

2.1. Study area and data collection

The study area (Fig. 1) is located in a catchment near the village of Vinchiana in the province of Lucca (Tuscany, Italy), where a number of shallow landslides have occurred. One of them resulting in

Fig. 1. Localization of the Vinchiana (Tuscany, Italy) case study and landslides map: black-lines landslide contours and in dark colour areas with $SF \leq 1$ estimated by the infinite slope model during the November 2000 event and in (Solco dell'Angelo and Piantone basin).

Table 2
Values of the parameters used for the inverse analysis considering three different conditions: saturated profile with basal root reinforcement only, saturated profile with lateral root reinforcement only, and unsaturated condition with lateral root reinforcement only. In imposed values are in bold and inverse calculated values are in italic.

Parameters		Measured values	Saturated condition		Unsaturated condition
			Inverse calculated values of basal root reinforcement only	Inverse calculated values of lateral root reinforcement only	Lateral root reinforcement only
Vegetation overload	$m_{veg.}$ [t/m^2]	0.071	0.071	0.071	0.071
Soil bulk density	γ [t/m^3]	1.4/2.1	2.1	2.1	1.5
Pore-water pressure	u [kPa]	(?)	**10**	**10**	*1*
Saturation	%	(?)	**100**	**100**	*10*
Soil cohesion	c [kPa]	0	0	0	0
Friction angle	φ [°]	33.4	33.4	33.4	33.4
Slope angle	β [°]	35	35	35	35
Lateral root reinforcement	$c_{lat.\ veg.}$ [kPa]	(?)	**0**	*90*	**14**
Basal root reinforcement	$c_{bas.\ veg.}$ [kPa]	(?)	*7.4*	**0**	0
Basal area	A [m^2]	≅600	≅600	≅600	≅600
Depth	h [m]	1	1	1	1

human casualties during a mild rainfall event on 19–20 November 2000 after very prolonged rainfall (three weeks' duration with a cumulative rainfall of 360 mm of return time period of more than 100 years). The back analysis carried out in this study focuses on a particular landslide that affected a small portion of the slope (area ~600 m^2) between the altitudes of 260 and 175 m.a.s.l. The mean soil thickness was about 1 m and slope inclination was about 35°. The mobilized sediments reached the main stream as a debris flow. Similar scenarios were observed for other shallow landslides in this area.

The site has a dominant vegetation cover composed of chestnut trees (*Castanea sativa* Mill.), managed as coppice wood, with the presence of black locust trees (*Robinia pseudoacacia* L.) and cluster-pines (*Pinus pinaster* A.). Tree species composition is dominated by chestnut trees (70%). In this region, the fruit chestnut crop lies on terraced slopes while the coppice wood generally lies on steeper slopes (like in our study area). Since the abandonment of land at the end of the 20th century, both types of tree covers are now present in forms going towards mixed and broad leaves woodland. Today, the fruit chestnut crop is characterized by a stem density of 120–150 plants per hectare. The mass of the vegetation on the landslide area was estimated with standard dendrometrical methods considering the neighbour forest stand as reference.

The climate is Mediterranean (Köppen classification). Geologically, the study area is a flysch formation (*Macigno*) composed of quartz and feldspar sandstone alternated with layers of siltstone. Such geologic formations create acid soils which differ as a function of slope angle: soils under fruit chestnut crop are classified according to Soil Survey Staff (U.S.D.A., 1998) as a sandy-clay-loam to a loamy-sand, subgroups *Dystric Eutrochrepts* on weak slope, and *Lithic Eutrochrepts* and *Lithic Udorthents* on steeper slopes. Measured pH values ranged between 4.4 and 4.7 in the A horizon and between 5.6 and 6 in the B horizon. Soil thickness varies between 35 and 110 cm; A horizon thickness varies between 5 and 35 cm. The dry and saturated soil bulk density was measured from undisturbed soil samples.

Shear tests in laboratory under saturated-drained conditions for three different confining pressures (50, 100, and 150 kPa) were carried out on rooted samples (root diameter 1 mm) to characterize the mechanical properties of the soil slip surface with and without roots. The friction angle was 33.4° with no cohesion (Table 2). Single root specimens were sampled and tested for tensile strength (Preti and Giadrossich, 2009) for the calibration of the root maximal tensile strength of different root diameter classes. Five infiltration tests with a double ring set-up were carried out to characterize the infiltration behaviour of the study area (Hillel, 2004). Values of saturated hydraulic conductivity range from 10^{-4} to 10^{-5} m/s, typical for sandy soils. Since the soil is well structured, we considered the upper layer of the slope to be well drained. Bulk density of soil is determined on core samples which are taken by driving a metal corer into the soil at the desired depth and horizon. The samples (the volume of which is known) are then oven dried and weighed. In addition to geotechnical data collection, root distributions were mapped for three chestnut trees and the data were used to calibrate the root distribution model. Table 2 shows the measured or assessed values.

2.2. Scaling of root reinforcement

The positions, dimensions, and species of 54 trees along the scarp of the Vinchiana landslide were recorded. This information was combined with pedological and eco-hydrological data to estimate the root distribution on the slope. In the absence of validation data for different species, we neglected differences between various species. Based on the root distribution information we calculated the maximal tensile strength of the bundle of roots at different distances from tree stem. Considering the different tree dimensions and distances from tree stems, the patterns of root reinforcement were calculated and visualized with a GIS program (ArcGIS from ESRI) on the entire slope. The raster cells have a resolution of 1 m^2. For the final calculation of root reinforcement we used the FBM and considered the peak tensile strength of the bundle of roots as representing the contribution of roots to lateral reinforcement. We extended the fiber bundle model proposed by Pollen et al. (2004) by introducing a strain step loading (instead of stress step loading) and considered variation in the root Young's modulus as a function of root diameter. An important aspect to keep in mind is that this peak value is reached at different displacements depending on the characteristics of the root distribution.

With this method we were able to quantify the variation in the maximum root reinforcement along the scarp (Figs. 2 and 4) based only on the trees standing on the slope; no information was available to reconstruct the original distribution of vegetation cover that existed prior to the landslide.

2.3. Slope stability calculations

We implement limit equilibrium assumptions for an infinite slope to compute slope stability (Coppin and Richards, 1990; Schmidt et al., 2001). The failure condition was quantified using the Mohr–Coulomb criterion. The inclusion of lateral root reinforcement in slope stability calculations was achieved by considering an additional stabilizing force proportional to the scarp surface and to the mean root reinforcement (Fig. 4).

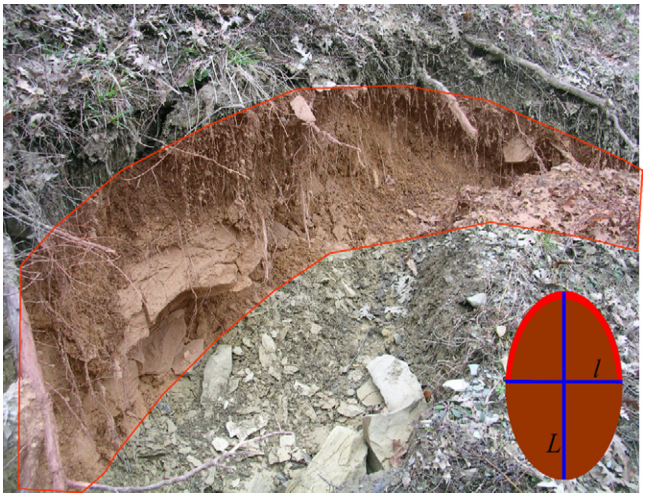

Fig. 2. Illustration of the lateral area of the scarp (in red) considered to influence the stability of the landslide through tensile root reinforcement. The lateral area is related to an elliptic shape with horizontal and vertical axes *l* and *L*, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article)

Additionally, we computed the force balance for different landslide shapes (varying the ratio between the two principal axes *L* and *l* in Fig. 2) and dimensions.

The standard formulation of the limit equilibrium equation for the infinite slope is

$$SF = \frac{A\tau_{bas.}}{F_{par.}} \tag{3}$$

where *SF* is the safety factor, *A* is the landslide area (m^2), τ is the shear strength at the slip interface (kPa), and $F_{par.}$ is the destabilizing force parallel to slip interface.

The modified formulation of the limit equilibrium equation for a safety factor *SF* considering lateral root reinforcement is

$$SF = \frac{A\tau_{bas.} + F_{lat.veg.}}{F_{par.}} \tag{4}$$

including the terms for lateral and basal forces, $F_{lat.\ veg.}$ and $\tau_{bas.}$, and the driving force $F_{par.}$. Below the expressions for the various forces and strengths are listed:

$$F_{par.} = [(Ah)\gamma g \sin\beta] + (Am_{veg.} g \sin\beta) \quad [\text{kN}] \tag{5}$$

$$F_{lat.veg.} = \frac{\text{lateral\_Area}}{2} c_{lat} \quad [\text{kN}] \tag{6}$$

$$\tau_{bas.} = c + \sigma^* \tan\phi' \quad [\text{kPa}] \tag{7}$$

$$c = c_s + c_{bas.veg.} \quad [\text{kPa}] \tag{8}$$

where

$$\sigma* = \sigma - u \quad [\text{kPa}] \tag{9}$$

is the effective normal stress.

- σ = total normal stress [kPa]
- u = pore water pressure [kPa]
- ϕ' = residual friction angle [°]
- A = basal area [m^2]
- h = soil depth [m], perpendicular to the slope
- γ = soil bulk density [t/m^3]
- β = slope angle [°]
- $m_{veg.}$ = weight of vegetation cover [t/m^2]
- c_s = residual soil cohesion [kPa]
- $c_{lat.\ veg.}$ = lateral root reinforcement [kPa]
- $c_{bas.\ veg.}$ = basal root reinforcement [kPa]
- g = gravitational acceleration [m/s^2]

The main assumption for the implementation of root reinforcement in the slope stability calculations is that roots along the scarp were subjected to similar displacement. In reality, roots on the upper part of the scarp are activated before roots located on the sides of the landslide scarp. Fig. 5 shows how lateral root reinforcement influences the stability of a landslide as a function of the landslide dimension.

The FBM was applied considering a series of static strain-controlled loading of a bundle of roots containing roots with different properties (e.g., Young's modulus and maximum tensile strength, which varies as a function of root diameter) to quantify the bundle stress–strain behaviour.

We considered infiltrating water into the profile to have a twofold effect on slope stability: increasing the soil bulk density (from 1.4 g/cm^2 in dry condition to 2.1 g/cm^2 in saturated condition) and weakening the shear strength of the soil material.

3. Results

3.1. Root reinforcement

Fig. 3 shows the value of root reinforcement for a hypothetical root distribution for the Wu model (modified by Wu et al., 1988) and the extended FBM as a function of pullout displacement. The WM estimation results in a constant value of reinforcement of about 38–50 kPa, while the result of the modified FBM shows a strong dependence on displacement and a maximal peak value of about 14 kPa.

The distribution of the maximal root reinforcement calculated with the FBM for the landslide scarp in Vinchiana is illustrated in Fig. 4. The values of maximal root reinforcement in the stand range between 0 and 100 kPa and between 5 and 25 kPa along the scarp.

3.2. Effects of lateral reinforcement

Figs. 5 and 6 show the results based on the implementation of lateral reinforcement in our model and its influence on slope stability. Results in Fig. 5 depict the force balance for different dimensions of landslides. The point where the two curves cross defines the dimension at which a slope become unstable. Fig. 6 presents the

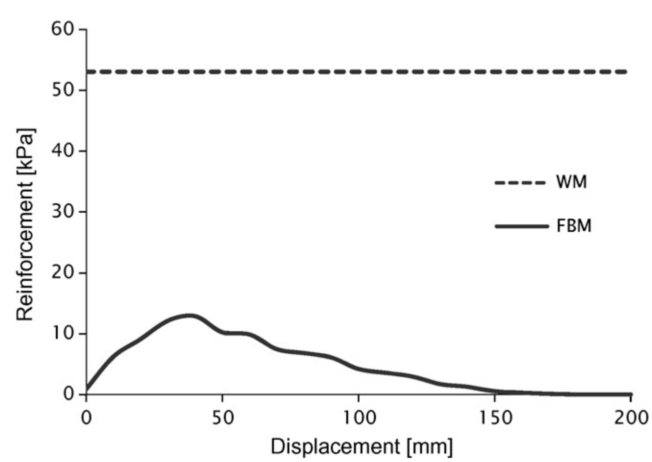

Fig. 3. Example of tensile strength of a bundle of root as a function of displacement. The graphic shows the difference between the use of the Wu model (Wu) and the fiber bundle model (FBM).

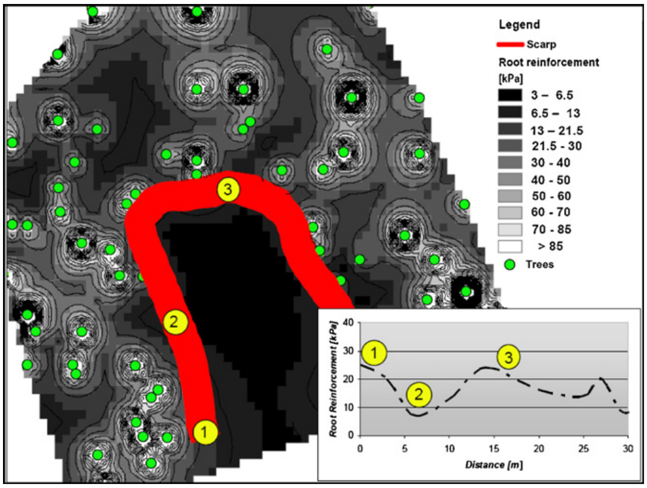

Fig. 4. Plan view of the root reinforcement distribution along the landslide scarp. Yellow circles help to locate the information in the inset; the inset shows the root reinforcement variability along the scarp calculated with FBM. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article)

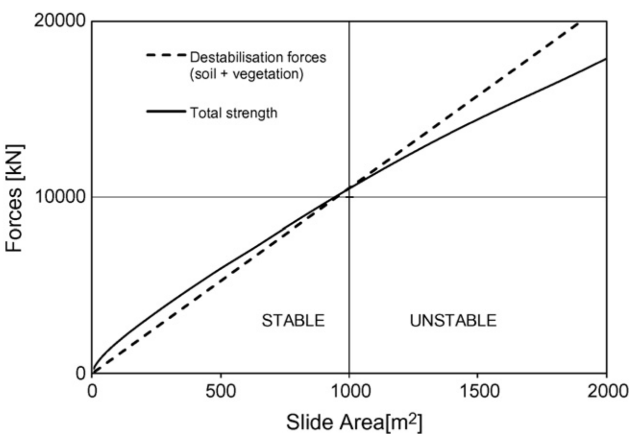

Fig. 5. Example of a force balance for an elliptical landslide (see Fig. 2) as a function of landslide dimension. The dotted and continuous lines represent the destabilization and stabilization forces, respectively.

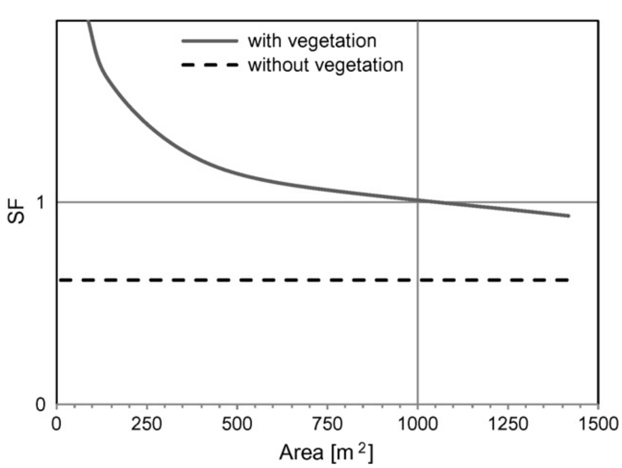

Fig. 6. Variation in the safety factor (SF) as a function of landslide area for an elliptical landslide assuming pore-water pressure of 1 kPa (saturation 10%), with and without vegetation. SF greater then 1 means stable, while SF smaller then 1 means unstable.

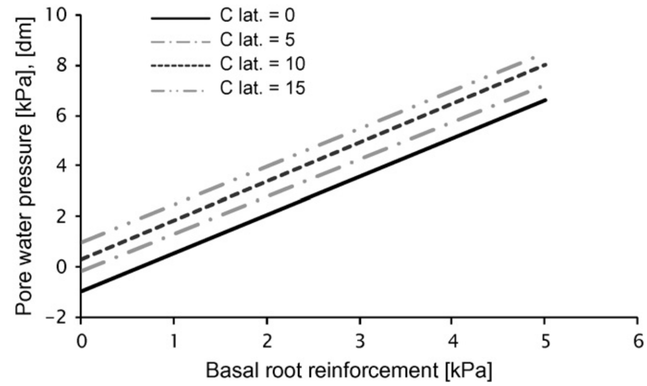

Fig. 7. Several combinations of back calculated values for root reinforcement and pore-water pressure in limit equilibrium conditions (SF = 1) for the Vinchiana landslide. Clat in the legend is the value of lateral root reinforcement in kPa.

same results in terms of variation in the safety factor (SF). This scenario is illustrated by plotting the value of SF versus hypothetical landslide dimension: the slope becomes unstable and a landslide occurs for size with a value of SF below 1.

3.3. Back analysis of pore-water pressure and root reinforcement

It is not surprising that the most uncertain values of the parameters used for the back analysis were those related to hydrology and root reinforcement. For the calculation we considered two scenarios: (1) and (1bis) complete saturation, and (2) unsaturated conditions using the mean estimated value of lateral root reinforcement (14 kPa). In the first cases 1 and 1bis we assumed that all the entire soil profile was saturated and we estimated (by inversion) the basal and the lateral root reinforcement, respectively, needed to attain the limit equilibrium. In the second case (2), we assumed that no roots crossed the slip surface and only lateral roots contributed to slope stabilization.

Table 2 (in italics) shows the measured values used for the analysis and the values of basal and lateral root reinforcement obtained from the back analysis. These values likely represent extreme conditions that could have taken place during the landslide. More realistically, the values of the parameters at the time of landslide triggering may have fallen somewhere in between calculated values for saturated and unsaturated conditions. Fig. 7 shows the critical pore-water pressure (resulting in SF = 1) back calculated for several combinations of parameters (basal and lateral root reinforcement values). Considering low basal root reinforcement because only a few roots crossed the slip surface, with lateral root reinforcement ranging between 10 and 15 kPa, we can identify from the graph a plausible combination of values which suggests pore-water pressures in the range of 0.5–3 kPa, corresponding to a seepage height of 50–300 mm with respect to the slip surface (5–30% saturation).

Table 2 values of the parameter used for the back analysis, considering three conditions: saturated profile with basal root reinforcement only, saturated profile with lateral root reinforcement only, and unsaturated condition with lateral root reinforcement only. In bold imposed values and in italics back calculated values.

4. Discussion

The introduction of the FBM concept for the quantification of root reinforcement in soils (Pollen and Simon, 2005) improved our understanding of the mechanical behaviour of rooted soils during failure. The FBM (Kun et al., 2007) used in this work gives results in accordance with data from literature for the quantification of the correction factor k'' (Table 1). A longstanding issue for the application of this approach to slope stability is limited availability of root distribution data. Field estimation of root distribution on vegetated slopes is difficult and better techniques are needed. Despite this shortcoming, the root distribution model used here was in good agreement with existing field data and was used to calibrate our model. Neglecting differences between tree species in the estimation of root distribution may have an important influence on calculated root reinforcement in specific situations. In our case study, however, the forest stand was dominated by Chestnut trees (70%) and thus variations among species may not play an important role in these particular slope stability calculations.

The absence of data for trees distribution and composition present on the slide area before the event would clearly result in an underestimation of root density along the scarp. This problem could be circumvented by increasing availability of airborne data (LiDAR, aerial photos, DEM, picture, etc.) or other types of inventories often collected in areas susceptible to landslides. In our case, we should keep in mind that the estimation of lateral root reinforcement is underestimated because we considered only the influence of the vegetation present on the upper part of the landslide scarp, and that the real values of lateral root reinforcement could probably range between 15 and 20 kPa (instead of the calculated value of 14 kPa) if the vegetation on the landslide would be considered too. Thus, pore-water pressure needed to trigger the landslide could reasonably have been as high as 2–4 kPa.

The simplifications made in the slope stability model may, on the other hand, cause an overestimation of the effects of root reinforcement and a consequent increased stability, as was previously discussed in Section 2.

Based on the calculations presented herein, about 1 kPa of mean pore-water pressure (saturation 10%) was required to trigger the Vinchiana landslide, a plausible value considering the amount of rain (intensity and cumulative) and the hydrological properties of the soil. The presence of an asphalted road about 100 m above the slide area contributed to the local amount of inflow, increasing the building up of pore-water pressure.

Under natural rainfall events, water may accumulate differentially in various locations on the slope resulting in local destabilization of different dimensions (based on subsurface conditions, local topography, etc.). This local hydrologically induced instability may be contained through lateral stabilizing forces to a certain dimension (volume or area) where additional increase results in failure and landslide triggering.

The use of the classical WM for estimation of lateral root reinforcement (Wu et al., 1979), would have resulted in overestimated stabilization forces leading to an error of about 10% in the calculation of the safety factor. This error would have increased exponentially for smaller landslides, as illustrated in Fig. 5. This error would be even higher with Wu's estimation for basal root reinforcement, particularly if this parameter exceeded 5 kPa. Not considering root reinforcement or suction, it would have required more than 1 kPa of mean basal cohesion (suction or cementation) to stabilize the landslide footprint.

If the lateral effects of root reinforcement or suction were omitted the result would be that the area needed more than 1 kPa of mean basal cohesion (either suction or cementation) to be stable.

It is important to point out that the maximum root reinforcement operates in a range of 0–5 cm of displacement (depending on the root distribution), while cementation or suction act at much smaller displacement (a few millimeters). This scale mismatch implies that root reinforcement acts at different time scales and has effects of different magnitudes compared to suction or cementation. In our case study, root reinforcements at different displacements have values between 0 and 20 kPa. Suction in sandy soils has values between 0 and 2 kPa when (tensile) displacement range is between 0 and 2 mm (Richefeu et al., 2007; Pierrat and Caram, 1997; Goulding, 2006). For displacement values exceeding 1–5 cm, soil strength imparted by root reinforcement is the primary lateral stabilization mechanism on scarp (see Fig. 3). On the slip surface the situation is different. The root reinforcement has to be added to the "residual shear strength" of the soil material and eventually to suction forces in the case of unsaturated conditions (but in the case of rainfall-triggered landslide we often have saturated conditions). Not considering dilatation–consolidation or cementation effects would influence the calculation in the range of small displacement (a few millimeters). In our case these effects do not influence the results because we consider a force balance calculation for displacement between 1 and 5 cm, which is a typical range of displacement at which rooted soils reach their maximum shear and tensile strength (Zhou et al., 1998). Assuming that the initial few centimeters of soil deformation are slow means we can neglect kinetic energy effects.

Considering that natural systems are continuously subjected to cyclic stresses (due to rainfall, snow melt, daily and seasonal temperature oscillations, atmospheric pressure oscillations, etc.) and that they adjust accordingly (at various time scales) to the new equilibrium conditions, we can imagine that different zones on a slope are under particular stress–strain conditions at different times. In the case of the Vinchiana landslide we can hypothesize that less than 2 cm of displacement were needed to reach the critical equilibrium of forces, because, under dry conditions, equilibrium would be reached at a root-soil strength corresponding to a displacement of about 2–3 cm (depending on local soil characteristics and root distribution).

5. Summary

In this work we discussed quantitatively the role of lateral root reinforcement in vegetated slope stability using the FBM formalism. A key outcome of the model is that we can quantify and interpret the overestimation of k'' often observed in calculations based on the well-known Wu model (Wu et al., 1979, 1988; Waldron and Dakessian, 1981).

The results of the slope stability calculations considering lateral root reinforcement show quantitatively the importance of this parameter in relation to the dimension of the landslide area. The stabilization effect of lateral roots was shown to be important for landslides with areas up to 1000 m^2 ($1.8 > SF > 1$) (see Fig. 6). This information provides guidance concerning the scale at which vegetation can contribute to lateral redistribution of destabilizing forces on the slope. Neglecting lateral root reinforcement would result in safety factors SF in dry conditions of 0.94 for landslides of any size.

Another important result of the model is the quantification of stress–strain behaviours of a bundle of roots. These stress–strain curves elucidate the role of root reinforcement in comparison with other factors such as suction, cementation, or soil friction. We show that root reinforcement acts in a range of a few centimeters of lateral displacement (depending on the root distribution) while suction and cementation act in a much smaller range of a few millimeters.

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