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THE ROLE OF ROOT REINFORCEMENT ON MAY 2002 SHALLOW SLOPE FAILURES IN ST. GIULIO CREEK CATCHMENT (NORTHERN ITALY)

IL RUOLO DEL RINFORZO ESERCITATO DALLE RADICI SUI DISSESTI SUPERFICIALI DEL MAGGIO 2002 NEL BACINO DEL T. S. GIULIO (ITALIA)

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ABSTRACT

In May 2002, many landslides triggered by prolonged rainfalls hit the territory of St. Giulio creek in Valcuvia (Varese, Northern Italy). The mass movements affecting the area during such event are mostly soil slips, which in some situation turned into catastrophic debris flows. In the study we estimated the values of soil total cohesion (soil cohesion + root cohesion) for a range of water table level by back-analysing one typical shallow landslide using the infinite slope model. The values were then compared with those obtained on the basis of field survey and laboratory tests, by the application of the model of Waldron (1977) and Wu et al. (1979) revised by Bischetti et al. (2002). The results show that root cohesion exerts a significant role on Valcuvia hillslopes stability, although it is not enough to balance high pore pressure consequences occurring in hollows during rare rainfall events.

Key words: shallow landslides; root cohesion, slope stability analysis

RIASSUNTO

Nel maggio 2002 il bacino del t. S. Giulio, in Valcuvia (Varese, Italia) è stato colpito da numerosi dissesti in corrispondenza di prolungate precipitazioni, che hanno causato numerosi danni ad edifici ed infrastrutture. I dissesti sono stati prevalentemente di tipo superficiale, ed in alcuni casi sono evoluti in colate detritiche. Nello studio, per un dissesto rappresentativo tra quelli verificatisi, è stata valutata la coesione complessiva (del suolo e delle radici) in corrispondenza di diversi stati idrologici del suolo attraverso l'analisi a ritroso utilizzando il metodo del pendio indefinito. I valori ottenuti sono stati confrontati con quelli ottenuti attraverso il modello di Waldron (1977) e di Wu et al. (1979), rivisto da Bischetti et al. (2002) parametrizzato mediante analisi di campo e di laboratorio. I risultati ottenuti mostrano che la coesione delle radici esercita un ruolo importante nella stabilità dei versanti della Valcuvia, ma non sufficiente a contrastare le elevate pressioni interstiziali che si creano nelle concavità durante piogge di particolare rilevanza.

Key words: frane superficiali; coesione delle radici, stabilità dei versanti

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INTRODUCTION

Superficial soil slips, triggered by heavy rainstorms or relatively moderate intensity but prolonged rainfall (Caine, 1980; Iverson, 1991; Crosta, 1998; Iverson, 2000; Borga et al., 2002), are a recurrent geological hazard in mountainous landscape. In spite of their small volumes, they are very dangerous because their susceptibility to evolve in debris flows, which impact human activities and infrastructures.
As a matter of the fact, a rainstorm in May 2002 hit Valcuvia (a left-hand tributary valley of the Maggiore Lake near Varese, Northern Italy), causing many landslides that involved the residual soils and till deposits that form a blanket of unconsolidated material overlying bedrock units, with a huge of damages to human activities (e.g. the local hospital has been evacuated and many roads interrupted, cutting many villages off).
The hillslopes of the valley are covered by a dense, but largely abandoned vegetation which often is proven to be not very efficient in terms of soil reinforcement. Although several field observations and experimental data have demonstrated the importance of tree roots for providing shear strength to shallow forested soils (e.g., Burroughs and Thomas, 1977; Waldron 1977; Abe and Ziemer 1991; Wu, 1995; Gray and Sotir 1996; Watson et al. 1999; Schmidt et al., 2001), in fact, the actual soil reinforcement depends on vegetation species, density, health and depth of the root system.
To understand the role of vegetation on the landslides occurred in Valcuvia, we studied one representative among the 15 soil slips that affected the forested areas of a sub-watershed of main valley, the St. Giulio creek catchment. On one hand we back-calculated root cohesion and his variation as function of water table depth; on the other hand we carried out field and laboratory measurements on roots to quantitatively evaluate the contribution of vegetation by means of a simple slope stability model (Bischetti et al., 2002).

GENERAL SETTINGS OF ST. GIULIO CREEK CATCHMENT

Study area

The study area of St. Giulio Creek is located near Cittiglio in Valcuvia, a left-hand flank tributaries of the Maggiore Lake (Varese, Northern Italy). Figure 1
St. Giulio creek basin is about 5 km^2 and it is characterised by a steep and highly dissected topography with typical V-shaped valleys; slopes commonly range between 25° and 45°. The outcropping rocks consist mainly of fine and coarse-grained limestone with interbeds of marl and nodular chert. The area, which glaciated several times during the Pleistocene and Holocene, has widespread, thick and mostly discontinuous glacial deposits; generally they consist of cobbles and gravel in a silty-sand matrix. Undifferentiated sandy residual and colluvial soils form a continuous blanket of 50÷100 cm, overlying till deposits and bedrock units.
In these recently disturbed terrains, forest is dominated by European beech (*Fagus sylvatica*), but there are intrusion of other species: Hazelnut (*Corylus avellana*), European white birch (*Betula pendula*), European ash (*Fraxinus excelsior*), Sycamore maple (*Acer pseudoplatanus*) in humid areas and hollows, and Red spruce (*Picea excelsa*) in non-native coniferous plantations.
The climatic conditions of St. Giulio creek catchment are typical of a Prealpine environment. Annual precipitation measured at the rain gauge of Vararo (in the upper part of basin; about 40 years of observations of the National Hydrographic service) is about 2330 mm. This area is really one for the most rainy of the Lombardy Region and precipitation fall as rainfall in autumn and spring principally, but during summer many heavy storms occurs.

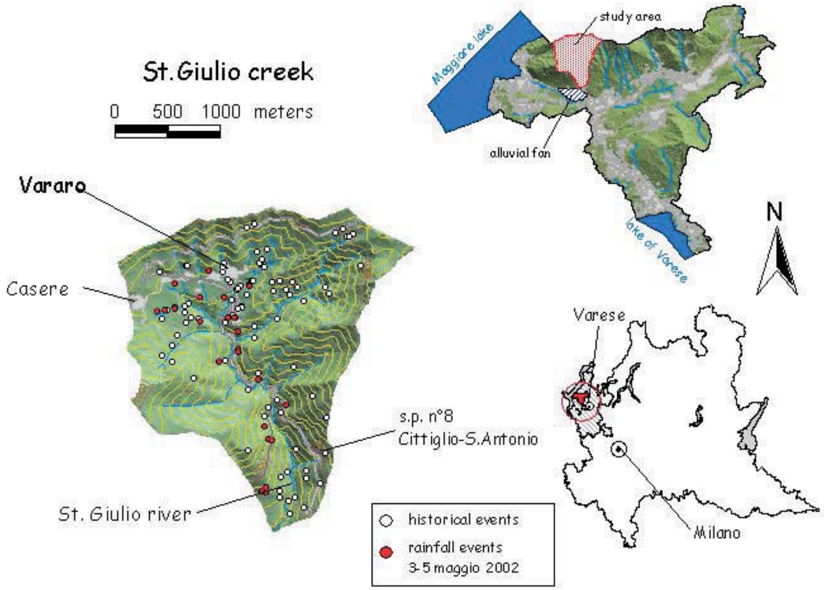

Fig. 1 – Location of the study area.
Fig. 1 – Area di studio.

Characterisation of the May 2002 soil slips

May 2002 had a high monthly precipitation of 520 mm (recorded at "Poggio S. Elsa" climatic station, about 1.5 km from the study area). In particular, a severe storm induced prolonged continuous rainfall for total duration of 3 days (about 200 mm). On 3 May a heavy rainfall of about 140 mm occurred, with a maximum of 20 mm/h. In April, the antecedent precipitation was about 100 mm.
During 3 May 2002 rainfall event many slope failures occurred, the most at middle and low positions on concave slopes, where natural drainage depressions are susceptible to instability because of accumulation of non-cohesive soil on steep slopes.
Among the many slips occurred, we considered a slope failure located on the right flank of the St. Giulio creek, at the bottom valley about 200 m North of the locality "I Mulini", along the road (SP n°8) from Cittiglio to Cuvignone Pass (1035 m a.s.l.). The selected mass movement could be described as *soil slip* and it was predominantly shallow and planar; it involved a rapid movement turned into debris flows and carried a great volume of mud, rock and wood fragments downstream to St. Giulio creek. In the area the outcropping bedrock was completely denudated.
The failure (Fig. 2) is 47 m long (L) and 5÷6.5 m wide (B) on a concave slope of average steepness 36°. The involved materials belong to the thin residual soils and to the underlying glacial deposits. The depth of the sliding surface is shallow with an average value of about 1 m. The main scarp of sliding head is steep (40-45°) and maximum height of 1.0 m (D). The derived breadth to length ratio (B/L) is about 0.14 and depth to length ratio (D/L) is 0.02. At

Fig. 2 – Studied shallow landslide.
Fig. 2 – La frana superficiale studiata.

605 and 615 m a.s.l. there are two minor scarps just over 50° steep, measured after the sliding. The volume of initial failure, indicated by complete soil profile removal from the main scarp area, is estimated to be just less 50 m^3.
The soil slip involved material consists of very poorly graded granular material, generally defined as a gravel-sand mixture with silty matrix. Natural water content is 9-11% between 0 and 50 cm deep, and rises to 19-23% between 50 and 100 cm deep. Dry unit weight is 13.5 kN/m^3 and friction angle (ϕ') is between 26 and 28 degrees; the soil has no cohesion.
The area surrounding this landslide is characterized by a convergent morphology (hollows) along the hillslope, suggesting a key role of water table rising in the failure. Many studies (Buchanan e Savigny, 1990; Montgomery e Dietrich, 1994), in fact, showed that pore pressures are higher in drainage depression than in the adjacent area as consequence of convergent subsurface flow.

BACK ANALYSIS

To evaluate the root-soil cohesion we carried out a back analysis on the selected slip adopting the infinite slope model (Skempton and DeLory, 1957; Nash, 1987). The model is very simple and soil is assumed to slide on a planar slip surface approximately parallel to the ground surface. In particular it's appropriate for wide, shallow slides with characteristic low values of the depth to length ratio (Crosta, 1998). Since the studied landslide is approximately 47 m long and the depth of the unstable soil is limited (maximum 0.8÷1.0 m), the infinite slope assumption is acceptable to analyse the problem.
At failure, the ratio between the shear strength and the shear stress is assumed to be unity, so the limit equilibrium equation can be rewritten to derive a value of total cohesion at failure:

$$C=\gamma_{sat} Z\cos^2\varpi\left(\tan\varpi-\left(1-m\frac{\gamma_w}{\gamma_{sat}}\right)\tan\phi'\right) \qquad (1)$$

where C is the total root-soil system cohesion, γ_{sat} is the saturated unit weight of soil, Z is the depth of failure plane, ω is the slope angle (and failure plane angle), ϕ' is the effective friction angle and the piezometric level is at mZ from the failure surface.

Since laboratory tests showed that soils has no cohesion, the total (C) and root (c_r) cohesion are coincident. Unfortunately the height of the water table at the time of failure is unknown, and we calculated the values of c_r for a range of possible water table heights. Table 1 shows the result for the failure plane assuming depth and slope of the shear plane of 1 m and 45°.

Tab. 1 – Values of c_r for a range of *m* values.
Tab. 1 – Valori di c_r per diversi valori di *m*.

m	c_r [kPa]
0.00	4.03
0.25	4.66
0.50	5.28
0.75	5.91
1.00	6.53
1.25	7.16
1.50	7.78
1.75	8.41
2.00	9.03

ROOT REINFORCEMENT MODELLING

The reinforcement model

Roots fixed in granular soil form a compound consisting of fibres of high tensile strength and adhesion embedded in a matrix of lower tensile strength (Gray and Leiser, 1982). The mechanical effect of the roots is to increase the confining stress and resistance to sliding and raise the strength of soil-root complex. In particular, assuming that roots are cylindrical, elastic and oriented perpendicular to the failure plane, shear strength increase can be simply written as (Waldron, 1977; Wu et al., 1979; Bischetti et al., 2002):

$$c_r = K \cdot t_R \qquad (1)$$

where K is a factor taking into account that roots are not perpendicularly oriented respect to the failure plane (k') and that not all root branches mobilize their maximum tensile resistance at the same time due to tortuosity, slipping, etc. (k''); t_R is the mobilized root tensile strength per soil unit area:

$$t_R = T_r a_r \qquad (2)$$

where T_r is the weighted average tensile strength per average root cross-sectional area, a_r is the root area ratio, computed as A_r/A, where A_r is the total cross-sectional area of all roots and A is the area of soil in the sample count.

Root tensile strength is affected as much by differences in size (diameter) as by species (Roering et al., 2002). The relationship between root tensile strength and diameter can be expressed in the form of a simple logarithmic equation as follows (Burroughs and Thomas 1977; Gray and Sotir 1996; Nilaweera and Nutalaya 1999; Bischetti et al., 2002):

$$T_r(d) = \alpha d^{-\beta} \qquad (3)$$

where α e β is empirical constants depending on species.

Since tensile strength is affected by diameter, equation (2) can be rewritten as:

$$t_R = \sum_{i=1}^{N} T_{r_i} \frac{A_{r_i}}{A} \qquad (4)$$

where N is the number of i diameter classes.

According to Schmidt et al. (2001) and with our own field observations we adopt a stability analysis model that includes root cohesion acting over both the basal surface and the lateral perimeter of landslide scarp. Along the lateral surface the cohesion is due to all the roots placed between the surface and the failure plane depth (*lateral root cohesion*), whereas on slip surface the resistance is given by the roots really pass through the plane (*basal root cohesion*):

$$c^{Z}_{r_{lat}} = \frac{\sum_{z=1}^{M}\sum_{i=1}^{N} \alpha d_{i,z}^{-\beta} a_{r_{i,z}}}{Z} \tag{5}$$

$$c^{Z}_{r_{base}} = \sum_{i=1}^{N} \alpha d_{i,Z}^{-\beta} a_{r_{i,Z}} \tag{6}$$

Where Z is failure plane depth, N is the number of class diameter, M is the number of depth class.

So, total root reinforcement, expressed as cohesion, depends on soil depth and is given by:

$$c_{r}^{Z} = K\left(c^{Z}_{r_{base}} + c^{Z}_{r_{laterale}}\right) \tag{7}$$

Evaluation of soil-root reinforcement in the landslide area

To estimate soil-root reinforcement available around the studied landslide, we have applied Equations (5), (6) and (7) to hazelnut (*Corylus avellana*) and European ash (*Fraxinus excelsior*), which represent the vegetation growing in the surrounding area.

As first step, live roots of the two species were collected for laboratory testing of tensile strength. Roots greater than 10 mm were excluded from the collection, according to previous studies which have indicated that bigger roots have a tensile strength greater than soil-root friction forces and they tend to slip before breaking (Burroughs and Thomas 1977; O'Loughlin and Watson 1979; Ziemer 1981; Schimdt et al., 2001). Testing was conducted with a model testing machine (projected and built by the Inst. of Agricultural Hydraulics) fitted with 0.5 kN or 5 kN, reversible, load cells. The relationship between root diameter and tensile strength for the tested species was then established using regression analysis; the resulting curves and regression equation are showed in figure 3.

The root area ratio values have been estimated by image analysis. On the landslide scarp we have positioned a frame 220 mm wide from the soil surface to the bedrock; roots inside the frame were cut and the portion of the profile was smoothed and wetted to give roots as visible as possible. Photographs were then taken and afterwards elaborated by a GIS software to correct geometrical deformation and to digitise all roots included in the frame; the distinction of roots belonging to hazelnut and European ash have not been feasible.

Digitised roots, finally, were analysed to evaluate diameter and root area ratio distribution with depth by increments of 10 cm.

In root area ratio evaluation, we neglected roots smaller than 1 mm in diameters and greater than 10 mm. Finer root tendrils, in fact, are short and tend to slip without contributing significantly to soil reinforcement; moreover they have a supporting function of vegetation in terms of nutrition and show a significant turnover (Gill and Jackson, 2000) which make their contribution uncertain. Bigger root, on the other hand, have a tensile strength higher than soil-root friction forces and tend to slip, mobilising only a little part of their tensile strength.

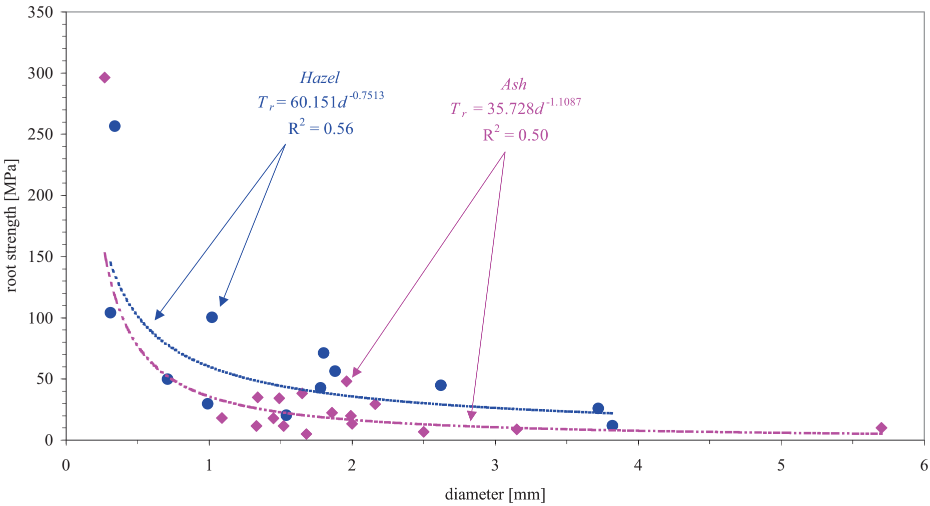

Fig. 3 – strength-diameter curves for hazel and ash.
Fig. 3 – curve sforzo-diametro per il nocciolo e il frassino.

The results obtained by our analysis (Figure 4) show a high concentration of roots in the first 30 cm, which dramatically decreases in the lower layers, up to the maximum root depth at about 90 cm.
As known, root area ratio is strongly influenced by land use management, vegetation density, climatic regime and, above all, local soil characteristics; in general root area ratio decrease with depth below the soil surface and with distance from tree trunk (Shields and Gray, 1992; Abernethy and Ruther, 2001; Bischetti et al., 2002). Root area ratio estimated at landslide

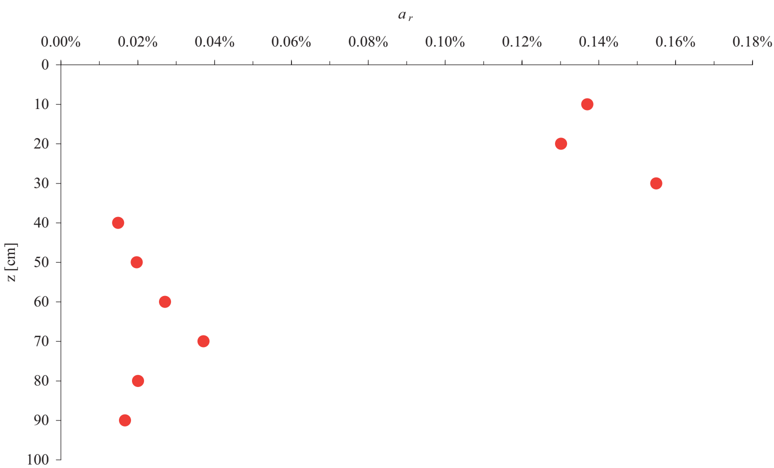

Fig. 4 – Root area ratio distribution with depth.
Fig. 4 – Distribuzione del rapporto di area radicata rispetto alla profondità.

scarp shows values comparable to other species for the shallower and deeper layers, but significantly lesser in the intermediate layers (Bischetti et al., 2003).
On the basis of tensile strength curves and root area ratio, we calculated total root cohesion by equation (7). Due to the impossibility to distinguish hazelnut roots from European ash ones, we calculated the tensile strength of each root diameter class as the average value of the two species; hazelnut and European ash, in fact, are equally distributed in the study area.
To apply equation (7), the sub-factor k' and k'' must be evaluated. The sub-factor k' can be expressed as:

$$k' = \cos\theta \tan\phi + sen\theta \qquad (8)$$

with θ angle of distortion of the deformed root respect perpendicular to the shear plane.
By means of a sensitivity analysis Waldron (1977) and Wu et al. (1979) showed that generally k' vary between 1.0 and 1.3 (40°<θ<70 e 25°<ϕ<40°) and generally the mean value of 1.15 is accepted (Wu et al. 1979). On the contrary, the reduction factor taking into account not all root branches mobilize their maximum tensile resistance at the same time during slope failure, k'', is not so widely accepted (Schmidt and others 2001). Among the few works which deal with the issue, Waldron and Dakessian (1981) in their experiments on barley observed a value of k'' of 0.83, whereas Hammond and others (1992) for forest trees suggest a value of about 0.56. The difference can be ascribed to the different size and branching of the roots belonging to the tested species: fine unbranched and uniform sized roots in Waldron and Dakessian (1981) tests, coarser, branched and uneven sized roots in Hammond et al (1992) case. As consequence, we consider appropriate in our case to fix the parameter k'' to 0.56.
Using root area ratio, root-strength values and the relationships (5), (6) and (7) then, lateral, basal and total root cohesion were calculated for the two studied species.
The results show that the root reinforcement drops off with depth below the soil surface as reported in table 2 and Figure 5.

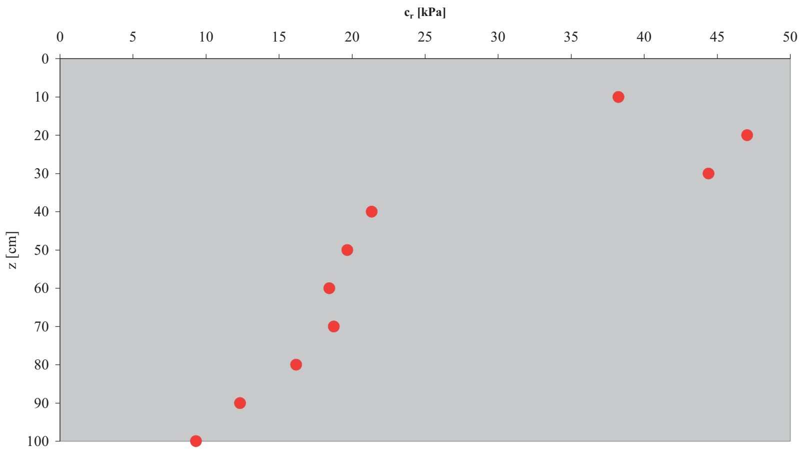

Fig. 5 – Root cohesion distribution with depth.
Fig. 5 – Distribuzione della coesione dovuta alle radici, rispetto alla profondità.

CONCLUSIVE REMARKS

During 3 May 2002 a long and relatively moderate intensity rainfall, triggered 15 soil slips in the St. Giulio creek basin; all the slope failures occurred at middle-low positions on concave non-cohesive soil and steep slopes. In such areas, as well known, convergence of surface and subsurface flow induce soil saturation and increase pore water pressure which, in turn, reduce effective normal stress making them susceptible to instability (Montgomery e Dietrich, 1994; Buchanan e Savigny, 1990).

The above considerations suggest that in S. Giulio creek catchment during 3 May 2003 event, the driving mechanism of sliding was an exceptionally high pore water pressure in the soil.

Tab. 2 – Soil-root cohesion values with depth.
Tab. 2 – Valori della coesione dovuta alle radici a differenti profondità.

z	$c^Z_{r_{base}}$	$c^Z_{r_{lat}}$	c^Z_r
10	18.18	18.18	36.35
20	24.09	21.13	45.23
30	21.14	21.14	42.27
40	3.73	16.78	20.52
50	4.60	14.35	18.95
60	4.91	12.77	17.69
70	6.13	11.82	17.95
80	4.67	10.93	15.60
90	1.82	9.92	11.74
100	0.00	8.93	8.93

Although we are not able to know the actual pore pressure value at the time of failure for the analysed landslide, due to the convergent morphology of the hillslope we expect that such an area would have already experienced near saturation hydrologic conditions, without sliding.

Results obtained by the back analysis carried out on the studied landslide (Table 1), show that for near saturated conditions (m=1) the hillslope stability (FS=1) requests a cohesion of about 6 kPa. Such a value can then be considered the minimum contribution exerted by vegetation on the stability of the hillslope.

By application of the root reinforcement model to the landslide scarp, the estimated root cohesion value at 1 m depth (the failure plane depth) is about 9 kPa (Table 2). Such a value represents the threshold value of total cohesion for a pore pressure corresponding to a piezometric level double of soil depth (Table 1). That corresponds to a very severe hydrologic condition that, however, is not so rare in hillslopes characterised by convergent morphology and/or covered by unhealthy vegetation (Johnson and Wilcock, 2000).

The contribution exerted by vegetation in the studied landslide, then, can be estimated between 6 and 9 kPa, and is agreement with published values which range from about 3 to 10 kPa (Sidle et al., 1985).

In conclusion, the contribution of vegetation in terms of root cohesion can play an important role in stabilising the forested landscape, especially in very steep hillslopes as in the S. Giulio creek catchment. On the basis of the results obtained in the present study, in fact, it appears evident that the presence of the root system of plants is a crucial factor to ensure hillslope stability on very steep slopes and/or in case of high water pressure into the soil induced by high intensity or long rainfall events.

Root networks, however, show a dramatic spatial variability in density and depth (Roering et al., 2002; Bischetti et al. 2003) as function of growth environment and management operations; as consequence the resulting reinforcement can be locally insufficient to ensure the stability.

The abandonment of forest, typical of many mountainous areas of northern Italy, then, make the landscape more vulnerable to shallow failures during prolonged or intense rainfalls and should be contrasted as a measure of landscape protection

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