Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2173

On the measurement of laboratory and field retention states of a loose coarse and vegetated topsoil

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ABSTRACT: The scientific literature widely recognizes the crucial role that the vegetation may play in controlling the infiltration of the rainfall at the ground surface, which then affects the changes of the overall equilibrium condition in slopes. However, the hydrological balance at the ground surface not only depends on the state and type of the vegetation and its root system, but it is also strictly controlled by the hydromechanical (HM) properties of the topsoil, which is likely to be in partially saturated soil condition. In particular, the soil water retention properties and the hydraulic conductivity function of the topsoil play a key role within the soil-vegetation-atmosphere interaction processes This study reports laboratory and field data of the retention states characterizing a coarse topsoil of an active debris flow, consisting of calcareous pebbles in a marly-clayey matrix. Furthermore, some woody roots, with diameters varying between 0.5 and 4.5 mm were also found in the soil samples collected in the field. The suction has been monitored in the field by using a Jet Fill tensiometer, whereas the measurements in the laboratory have been conducted by means of a small tip tensiometer. The retention properties of the material have been tested both along drying and wetting paths, with the aim to determine both the main drying and main wetting path and to investigate the hysteretic behaviour of the topsoil, which is of peculiar relevance in the HM processes within the soil-vegetation-atmosphere interaction. Both the laboratory and field data have been then used to validate one of the formulations proposed in the literature to derive the soil-water retention curve (SWRC), on the sole basis of the grain size distribution. The Kamiya and Uno (2000) method was tested for this purpose, and it resulted to be effective in predicting the SWRC for the topsoil under investigation.

KEYWORDS: Paper template, instructions.

1 THE CASE STUDY

In the last decade, two intense debris flow phenomena occurred in the Mount Sibillini National Park, upstream of the village of Nottoria in the south of Norcia (Perugia, Central Italy), after rainfall events. The debris-flow deposit overlays a carbonate complex consisting mainly of dolomitic limestone and massive limestone formations (bedrock). At present, the debris propagation channel shows evident signs of erosion, with furrows up to 2 m deep that have been shaped by water runoff and material mobilisation. The slopes surrounding the debris flow source area are also made by coarse-grained material originated by the alteration of limestones.

To the Authors' knowledge, except for the main debris flow events, no instability phenomena of such surrounding slopes delimiting the propagation channel have been observed in the recent years. However, in the years preceding the debris-flow events, large areas of vegetation were subjected to intense and prolonged cutting. In our opinion, this may represent a critical issue, and it prompted the launch of an experimental study, currently in progress, which aims to quantify the role of vegetation cutting in activating shallow landslides that - for the case study at hand - might contribute to sediment recharge in the source area of the debris flow phenomena. Some preliminary results of the study are published in Lepri et al. (2025) and Fraccica et al. (2025).

The paper presents and discusses the retention properties of the vegetated/bare topsoil of such debris flow deposit in partially saturated conditions. The specific focus is on investigating the role of vegetation in controlling the hydro-mechanical behaviour of the material under investigation.

2 MATERIALS

2.1 *Soils*

The material constituting the debris flow deposit as well as the surrounding slopes is made of calcareous pebbles of various sizes distributed in a sandy matrix. According to the USCS classification, the grain size distribution ranges from well graded gravel (GW) to well graded sand (SW), with average D_{50} = 4 mm and D_{10} = 0.35 mm. The material is composed of very angular grains. Based on the values of minimum and maximum voids ratio, the soil density is medium-low corresponding to in situ voids ratio in the range 1 – 1.5 (Fraccica et al., 2025).

The saturated hydraulic conductivity is estimated by following the classical Kozeny-Carman model (Kozeny, 1927, 1953, Carman, 1937, 1956), i.e.:

$$k_{sat} = C_k \frac{g}{\nu} \frac{n^3}{(1-n)^2} D_{10}^2 \tag{1}$$

where ν is the fluid kinematic viscosity (= 0.89×10^{-6} m^2/s at T = 25° C for water), coefficient C_k = 1/180 (from flow in capillary tubes) and n is the soil porosity (Wang, 2017). By assuming a value of porosity $n = 0.5$, equation (1) leads to a (high) value of $k_{sat} = 3.75\times10^{-3}$ m/s.

2.2 *Roots*

The forest on the study site is mainly composed of beeches, with a rare presence of oaks. In order to correlate soil hydro-mechanical behaviour to vegetation presence and removal, roots morphology was characterized by small trenches in the soil. Within this preliminary study, roots at the depth of suction measurements are presented. Root diameters, lengths and normalized volumes (root volume ratio $R_v = V_{roots}/V_{soil}$) are affecting soil hydraulic behaviour (Cecconi et al., 2025; Capobianco et al., 2025; Fraccica et al., 2024, 2019; Leung et al., 2023; Ng et al., 2016; Tagarelli et al., 2024). The roots were retrieved from the soil samples by sieving all the material with a 2mm opening sieve. Retained soil particles were removed by hands, in order to leave the roots only. The roots extracted from the given depth were put on a white background and photographed, jointly with a ruler, to calibrate the images from pixels to mm (Figure 1a). Thresholding the images with the *default* method in ImageJ (Schindelin et al., 2012) allowed to isolate roots (white) from the background (black, Figure 1b). The ImageJ plugin *analyze particles* allowed measuring average lengths ($l_{root,i}$) and diameters ($d_{root,i}$) for each one of the roots numbered in Figure 1b. Root volumes were then calculated as:

$$V_{root,i} = \frac{\pi d_{root,i}^2}{4} l_{root,i} \tag{2}$$

while the root volume ratio R_v was evaluated as:

$$R_v = \frac{\sum_i V_{root,i}}{V_{soil}} \tag{3}$$

For the case in Figure 1, the root volume ratio calculated is $R_v = 0.008$ (0.10 m below ground level), which is in good agreement with the values presented by Bischetti et al. (2009).

Root volumes and lengths were summed and grouped as a function of diameter ranges, as shown in Figure 1c. As it is possible to observe, roots with diameters from 1.0 mm to 1.5 mm are the more frequent and contribute significantly to the overall root length and volume. Considering that the soil of this study has an average grain size $D_{50} = 4$ mm and an average pore size $x_{50} = 0.30 \times D_{50} = 1.20$ mm, as proposed by Kamiya and Uno (2000), roots' diameters are comparable to pore sizes. Hence, while they grow, the main mechanism of development in length is the displacement (or rotation) of grains, increasing the number of fissures and macropores of the matrix (Anselmucci et al., 2019; Fraccica et al., 2024). Finally, some thick roots (i.e. with diameters between 2.5 and 4.5 mm) were observed: these are significantly contributing to an increase in the overall volume of the root architecture while marginally contributing to total lengths.

2.3 *Rooted soils*

The shear strength properties of investigated rooted soils were evaluated through direct shear tests performed on remoulded samples at increasing stress levels $\sigma_v = 50 - 400$ kPa (Lepri et al., 2025; Fraccica et al. 2025). Completely dry and fully saturated (sat) conditions were explored, and the transitional behaviour from dry to sat conditions was observed by following wetting paths upon shearing. The stress-strain behavior of rooted soil was found to be ductile at all applied stress levels and to be moderately dilatant at low vertical stress with an observed gentle peak. Generally, values of shear strength were observed to be about 30-50 % larger than the unrooted soil (bare). For the material belonging to the debris flow deposit shear strength parameters in dry and sat. condition do not significantly differ, while dry rooted soils from the surrounding slopes exhibit a larger frictional strength than that observed for the saturated rooted soil. Roots induced an increase in cohesion despite providing a less dilatant volumetric behaviour upon shearing with respect to the bare soil (Lepri et al., 2025). The following Table 1 summarizes the shear strength parameters of rooted soils from the investigated area.

Table 1. Average values of shear strength parameters obtained from direct shear tests on investigated rooted soils (from Lepri et al., 2025 and Fraccica et al. 2025).

parameter	symbol	average value	unit
peak friction angle	ϕ'	36	°
cohesion	c'	30 - 50	kPa

Figure 1. a) original image of roots; b) image analysis for root identification and size measurements (black and white threshold + analyze particles in ImageJ), c) histogram of total root lengths and volumes as function of root diameter ranges obtained from image analysis of a) and b).

3 SOIL WATER RETENTION PROPERTIES

The hydraulic behaviour of the SW debris has been investigated solely in terms of its water retention properties. No saturated hydraulic conductivity measurements have yet been conducted on the material, as these are currently ongoing in the laboratory to verify the reliability of the k_{sat} estimation as a function of void ratio and D_{50}. Accordingly, the retention states of the material under partially saturated conditions were explored along a drying path in the laboratory using a tip tensiometer. Bare soil specimens retrieved from the debris flow deposit were reconstituted at a void ratio $e = 1$. Retention measurements on vegetated soil were performed in the field using a ceramic tip tensiometer. Gravimetric water content was determined by oven drying.

Water retention predictions were made from an average grain-size distribution (GSD) curve of the material of the study, using the approach proposed by Kamiya and Uno (2000) with a shape factor of particles K_s = 10, representing a soil with angular shape grains. Predictions are in good agreement with measurements.

A fitting of the bare soil retention states, considering both the laboratory measurements and the predictions obtained from Kamiya and Uno (2000) was carried out through the SWRC law proposed by Van Genuchten (1980):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1+(\alpha s)^{n^*}\right]^{m^*}} \; ; \; m^* = 1 - \frac{1}{n^*} \qquad (4)$$

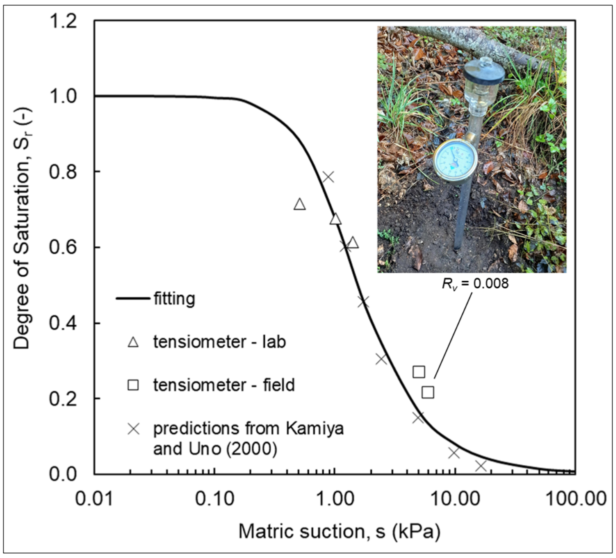

Figure 2. Soil water retention curve for bare soil. Vegetated soil field measurements included

where θ, θ_r and θ_s are the volumetric water content, the residual one (assumed equal to 0 for a SW – GW) and the one at saturation (θ_s = n when Sr = 1), respectively. α, n^* and $m^*$are fitting parameters obtained as a result of best fitting.

Despite being few and preliminary, vegetated field measurements lie very close to the bare soil curve, suggesting that limited effects can be expected by roots in this loose and coarse-grained soil. Moreover, results are in line with Fraccica et al. (2024) which showed limited effects of a R_v = 0.008 on the soil water retention curve of a clayey sand.

By using the saturated hydraulic conductivity value derived for the material (discussed in Chapter 2) and adopting the Mualem–van Genuchten model (Mualem, 1976; van Genuchten, 1980), it is possible to employ the van Genuchten parameters obtained from best-fitting procedures to construct the hydraulic conductivity function. This function describes the variation in the material's hydraulic conductivity under partially saturated conditions (Fredlund and Rahardjo, 1993). Such a function is particularly relevant for hydraulic calculations of rainfall infiltration through the soil. Although these calculations have not yet been performed, they will be carried out in the future to evaluate the meteorological conditions under which landslide initiation is expected.

Figure 3 presents the resulting hydraulic conductivity function, which indicates a significant decrease in hydraulic conductivity with increasing suction, especially once the so-called air-entry value is exceeded; in this case, it is slightly below 1 kPa. This hydraulic characterization will be enhanced by laboratory measurements of saturated hydraulic conductivity using a permeameter, testing both rooted and non-rooted samples, in order to determine whether the root system produces significant changes in hydraulic conductivity, as is expected (Fraccica et al., 2024; Tagarelli et al., 2023).

In addition, the water retention properties of the material will be further investigated in the laboratory by measuring the retention behaviour along both drying and wetting paths, again comparing rooted and non-rooted conditions.

This complete dataset will be on the whole essential for performing landslide susceptibility scenario analyses for the material under different conditions, and for quantifying the role of vegetation.

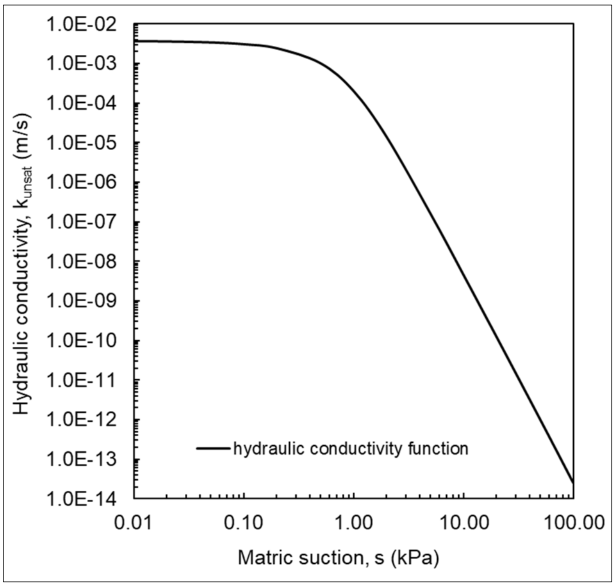

Figure 3. Hydraulic conductivity function derived from the soil water retention curve for bare soil (Figure 2), adopting the Mualem-van Genuchten formulation (Mualem, 1976). The value of the k_{sat} adopted is obtained from the Kozeny-Carman model.

4 CONCLUSIONS

This study presented preliminary findings from research aimed at assessing the potential role of vegetation cutting as a predisposing factor in slope instability near the source area of debris flow.

Laboratory investigations revealed significant natural heterogeneity in the physical properties of soil and roots, which complicated direct comparisons between the area affected by vegetation cutting and the control area.

An average soil water retention trend was established for bare soil using both laboratory measurements. Vegetated retention measurements were carried out in the field. So far, negligible differences have been observed between vegetated and bare soil but further measures are foreseen. Further in-situ monitoring is planned to identify possible differences in hydraulic behavior resulting from vegetation cutting and root decay. In particular, the study will explore whether root decomposition contributes to the formation of preferential water flow paths, potentially accelerating suction loss and reductions in soil shear strength during rainfall events.

Such changes in hydraulic behavior, combined with a decrease in mechanical root reinforcement, may contribute to shallow landslide susceptibility in the study area.

5 ACKNOWLEDGEMENTS

This study has been funded through a project under the Italian National Recovery and Resilience Plan (NRRP).

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