IN SITU AND LABORATORY INVESTIGATION OF THE SATURATED HYDRAULIC CONDUCTIVITY OF A CLAYEY SOIL COVER WHEN BARE OR VEGETATED

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Summary

The aim of this research has been to investigate the effects of rooted soil on the saturated permeability (k_{sat}) when compared to the bare condition. In particular, the hydro-mechanical properties (HMP) of the soil have been investigated in term of both retention properties and saturated permeability, as well as the principal root traits. The retention states of the material have been investigated by means of the filter paper technique in the laboratory. As for the saturated permeability, laboratory (i.e., modified permeameter) and in-situ testing have been conducted (i.e. Guelph's permeability test). Furthermore, in-situ evaluation of the wetting front during the in-situ test has been evaluated through capacitive probes installed nearby.

1. Introduction

Recently, the soil-vegetation-atmosphere (SVA) interaction is becoming a subject of intense scientific research within the geotechnical community; this is because the SVA interaction has been recognized to induce significant pore pressure variations in slopes, at both shallow and larger depths, being responsible of landslide activity. Indeed, the cause-effect relationship between the current activity of landslides and the SVA interaction has been characterized based upon both phenomenological and the numerical diagnoses [1].

All the processes influencing such interaction are of different nature and determine the chemo-thermo-hydro-mechanical transient boundary conditions at the slope ground level, i.e. within 3-4 metres depth, where the liquid, gas, and energy exchanges with the atmosphere and the vegetation are of maximum intensity. Hence, the thermo-hydro-mechanical constitutive properties of the materials by this depth, as well as the vegetation properties, are of key relevance within slope scale thermo-hydro-mechanical balances affecting the slope stability [2]. This paper is intended to contribute to the hydro-mechanical characterization of a clayey soil cover for advancement in the modelling of the SVA interaction, in turn influencing the weather-induced landslide activity. Data from both field and laboratory campaigns have been acquired and analyzed for a heterogeneous clayey soil cover when either rooted or bare. The results are wished to provide indications of the evolution of the HMP related to the roots network. The clayey soil samples have been taken in-situ on a slope where deep-rooted species were seeded and farmed within a crop test [3].

1.1 Slope scale processes in the Geo-Hydro-Mechanical context of reference

All the field and laboratory data reported hereafter refer to the Pisciolo case history, which represents a prototype of the south-eastern Apennine slopes, location of landslides whose current activity relates to the slope–vegetation–atmosphere interaction (SLVA; [4a, b]). Pisciolo hillslope, nearby Melfi, is located on the right side of the Ofanto River valley. The elevation at the site ranges from 292 to 412 m above sea level (m asl) and the hillslope is characterized by a slope inclination ranging from 8 to 30 %, with an average value of 12%. The hillslope is partially devoted to agriculture, with the growth of wheat, whereas spontaneous seasonal vegetation is present in the surrounding area. The hillslope is made of structurally complex fissured clays, classified as F1/I5-I6 according to [5], which have been characterized by [4a]. They are involved in an active deep roto-translational multiple landslide [1], [4a].

1.2 Test site

At the toe area of the roto-translational multiple Pisciolo landslide, an extensive field and laboratory investigation campaigns were carried out to characterize the hydro-mechanical behaviour of the clayey soil cover (20%<CF<60%), down to 7.5m depth.
An area of about 2000 m^2 was seeded with a selected deep-rooted vegetation, with the aim of assessing the efficacy of some peculiar deep-rooted species in modifying the infiltration balance of the soil cover [3]. The selection of the species and the seeding of the crop were carried out by the Italian company “PratiArmati s.r.l.”, through an innovative green technology, which has been used, so far, only to mitigate rainfall-induced erosion [6a, b]. The test area has been equipped with several sensors, in order to investigate the transient infiltration processes. [3] Present the field equipment and an initial phenomenological interpretation of the monitoring data, providing the retention (AEV in the order of 1000 kPa of suction) and permeability ($1*10^{-9}< k_{sat} <1*10^{-12}$ m/s) properties of both the rooted and the bare soil cover, along with the corresponding seasonal evolution of the humidity and suction profiles, relating to the SVA interaction.
In particular, in November 2017 they were seeded both *Gramineae* and *Leguminosae*. Perennial *Gramineae* are characterized by a gravitropic vegetative growth and make the root system uptake water and nutrients at a significant depth below ground level, firmly anchoring the plant into the ground [7]. The *Leguminosae*, which do not belong to the “evergreen” microthermal species, have been instead seeded mainly to provide nitrogen nutrients to the soil, according to the carbon fixation pathway named “C3 carbon fixation” [8].
To compare the HMP of the vegetated and the bare soil cover, the sampling and monitoring have been carried out both within the vegetated and outside, i.e. where spontaneous sparse vegetation occurs.

2. Testing Method

2.1 Laboratory testing

The geotechnical characterization was based on laboratory testing of both undisturbed and disturbed samples collected within the soil cover down to 0.50 metres depth, located either inside or outside the vegetated area, for comparison of the HMP under different root system features. The soil composition has been characterized through geotechnical index testing. The HMP of soil have been assessed by carrying out both drying-wetting and permeability tests. The soil samples were collected using a manual auger (50-56mm diameter, 50 mm height) in the well dug, both inside and outside the vegetated area. A further experimental and theoretical investigation will be performed to check the representativity of the sampled soil volume.
The retention properties have been measured in the laboratory by means of the filter paper technique. Whatman No. 42 filter paper was used to measure the matrix suction [9]. For each measurement, a couple of filter paper disks were put in contact with each of the two specimen bases. An equilibration time of two weeks was guaranteed and the calibration curve deduced by [10] was used. From the four filter paper disks, one average suction value was deduced.

The saturated permeability coefficient, k_{sat}, has been determined at the specimen scale (56 mm diameter and 20 mm height) by carrying out constant permeability tests. Confining stress was adopted comparable to the in-situ stress condition.
In addition, the determination of root density has been carried out. Then, after the assessment of the WRCs, the separation of the roots from the soil samples has been done in the laboratory by hand sieving (USDA procedure) with a mesh of 40 (ASTM standard). The root length has been evaluated by means of RhizoVision Explorer [11]. This open-source software extracts phenotypic traits from plant root images acquired using either flatbed scanners or digital cameras and performing image processing operations. Root length was referred to unit soil volume as root length density (RLD). The root dry weight was not determined, as it is not a suitable indicator of the plant absorption capacity. This is because thin roots are the most physiologically active and represent a very low weight percentage of the whole root system.

2.2 In-situ testing

Also, in-situ tests have been carried out at the Pisciolo hillslope to determine the saturated permeability. The saturated permeability coefficient, k_{sat}, was measured through hydraulic conductivity tests carried out using the Guelph permeameter on 6/05/2021 and 29/03/2022, inside and outside the vegetated test area. The testing procedure prescribes the application of a steady-state rate of water recharge into the unsaturated soil cover inside a surficial cylindrical well hole, in which a constant head of water is kept. Once a steady state condition of the seepage in the soil is reached, the constant water flow rate is used to compute k_{sat}. The Guelph-Richards procedure [12] offers a solution of the Richards equation applied to the water flow from the well located in the vadose zone. k_{sat} has been computed either using the single head approach [13] or the simultaneous equation approach [12], making reference to different imposed heads: h_1=15cm and h_2=25cm.
Volumetric water contents have been logged down to 1.6m depth at 10cm spacing, using a soil capacitive sensor probe [14], aiming at evaluating the moisture variation over time, as the effect of the propagation of the saturated bulb surrounding the well dug (30cm far from the sensor probe) during the tests.

3. Results and discussion

In Table 1, the main physical properties of the soil samples, both inside and outside the vegetated area, named respectively inside (I) and outside (O), are listed. The granulometry of the rooted samples (I) allows classifying the material as sand with clayey silt, whereas the O samples as silt with clayey sand (AGI 1994).

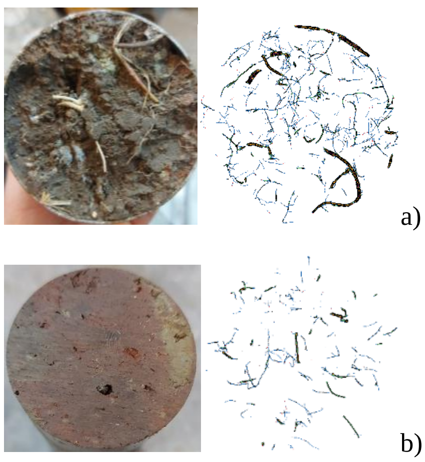

Table 1. Physical properties of the soil samples inside and outside the vegetated area.

	Inside (I)		*Outside (O)*	
	1° test	2° test	1° test	2° test
CF [%]	14.99	17.39	12.20	11.14
MF [%]	31.22	38.69	48.40	44.60
SF [%]	53.80	43.92	39.40	44.26
Unit weight in dry state [kN/m³]	15.58	14.91	14.50	15.42
Natural water content [%]	17.87	22.76	29.47	26.08
void ratio e [-]	0.70	0.78	0.83	0.72
saturation degree, S_r [%]	68.55	78.69	95.85	97.60
Suction, s [kPa]	589	532	106	78

Fig 1. Undisturbed Sample and corresponding results of the root image processing a) Inside and b) Outside the vegetated area.

Three I samples and two O samples have been subjected to the root analysis for the RDL determination. The root density length (RDL) of the I samples (Fig. 1a) has been found to vary in the range of 1.4÷3.5 cm*cm^{-3}, whereas it ranges between 0.6÷0.8 cm*cm^{-3} for samples O. The size of the RDL varies for either I or O samples, depending on both the spatial root density variability and different stages of the year in which sampling was carried out. The values are in agreement with those found among the grass species [15]. Fig. 3b shows that the majority of the diameter of the root is in the range of 0.5-1mm. Root diameters of less than 0.5mm were also found. However, for the range between 1-2mm and 2mm above, the I samples showed the highest values.

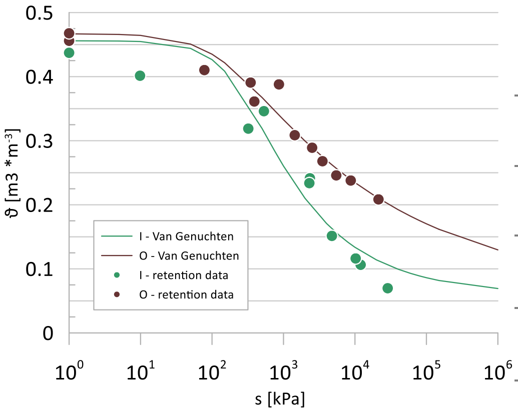

Table 2. Van Genuchten parameters and k_{sat} values determined in situ and laboratory, inside and outside the vegetated area.

			I	*O*
Θs	*[m3/m3]*		0.456	0.467
Θr	*[m3/m3]*		0.06	0.06
α	*[1/m]*		0.041	0.0675
n	*[-]*		1.456	1.201
K_{sat} 1° test	*[m/s]*	Single head (sh)	2.24*10^{-07}	9.04*10^{-09}
		Double head (dh)	1.09*10^{-06}	8.85*10^{-08}
K_{sat} 2° test	*[m/s]*	Single head (sh)	1.12*10^{-07}	1.16*10^{-09}
		Double head (dh)	4.20*10^{-07}	-
K_{sat} permeameter [m/s]			1.20*10^{-07}	1.40*10^{-09}

Fig 2. Water retention measurements with reference to both Inside the vegetated area and Outside of it, together with their corresponding WRC (drying and wetting points are joined into a unique dataset).

The ϑ_w-s data logged in the laboratory tests for samples I (Fig 1a) are shown with green full dots in Fig. 2. These are compared with the retention data for the O samples (Fig 1b), shown with brown full dots in the same Figure. The corresponding WRCs are shown as green and brown lines respectively in Fig. 2. The fitting parameters were evaluated through the RETC Code Vers. 6.02 according to [16] and are reported in Table 2 with reference to both WRCs.

The data shown in Fig. 2 suggest that the undisturbed specimen I has a lower retention capacity than specimen O. The ϑ_s of the rooted samples, I, are only slightly lower than that of the O sample. Moreover, for the rooted soil, the α parameters decrease with the addition of vegetation roots, whereas a higher n indicates a more uniform pore size distribution [17].

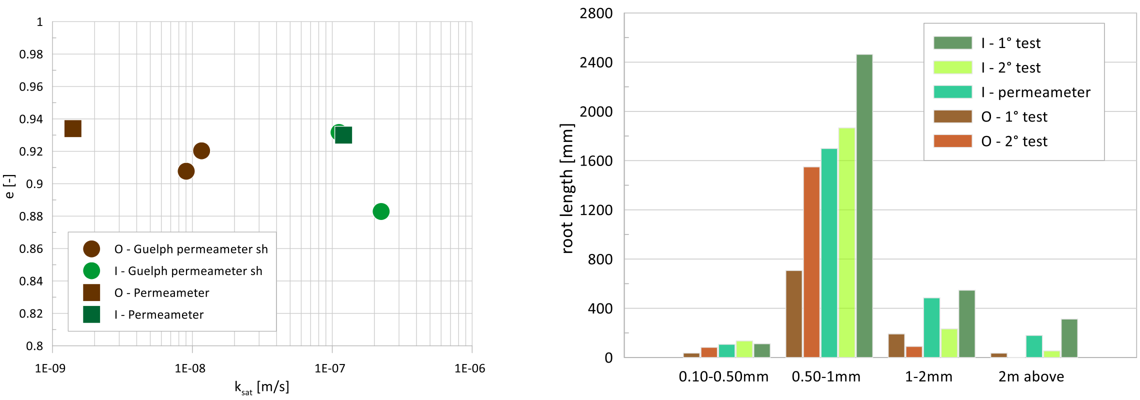

Fig 3. a) k_{sat} values determined in situ (sh) and laboratory, inside and outside the vegetated area. b) root diameter class found within the soil samples analyzed.

The results show that the plant roots affect k_{sat} too (Figure 3a; Table 2): the measured coefficients for the O samples are in the range of 1.16*10^{-09}<k_{sat}< 8.85*10^{-08} m/s and k_{sat} of 1.40*10^{-09} m/s, from in-situ and laboratory

tests respectively, whereas for the I samples the corresponding ranges are $1.12*10^{-07}<k_{sat}<1.09*10^{-06}$ m/s and k_{sat} of $1.20*10^{-07}$ m/s. This discrepancy, highlighted by both laboratory and in-situ tests, could be explained as the effect of macro-pore formation and/or preferential flow induced by roots. It must be underlined, however, that the type of root and plant growth influence k_{sat} in a combined way [11].
It is also evident from Fig.3a that the in-situ measurements give coefficient values higher than those resulting from the laboratory tests. This circumstance may rely on the different scales of detection related to the different adopted techniques, a problem which should be emphasized for rooted soils.

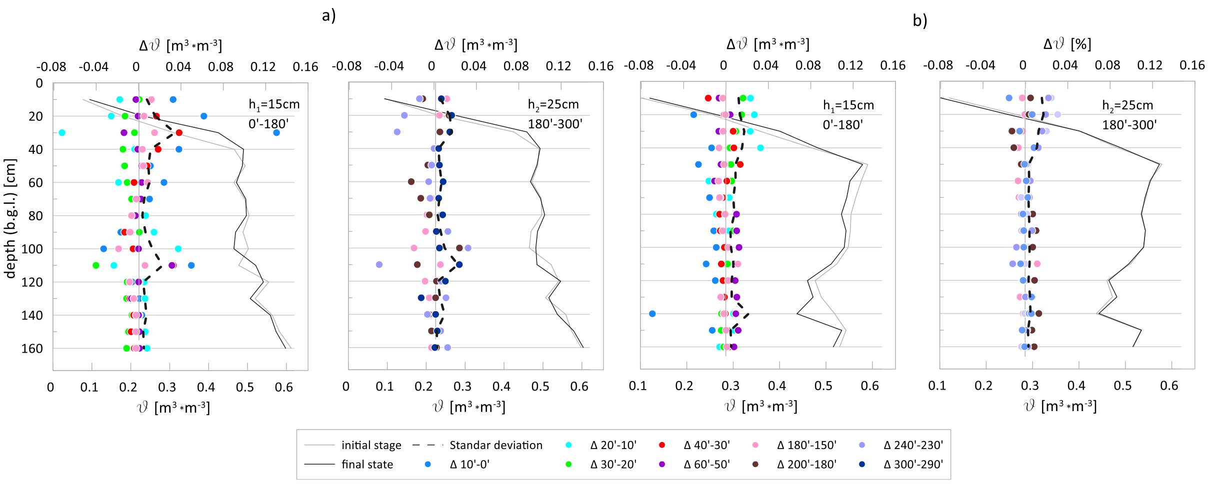

Fig.4 Volumetric water content profile and its variation for the first test. a) Inside and b) outside the vegetated test area.

To provide a comprehensive view of the wetting path to which the soil has been subjected during the first Guelph's permeameter test, inside and outside the vegetated test area, the volumetric water content profile, and its variation over time have been reported with depth in Figure 4.
The water content profiles before the start of the tests (grey lines in Figure 4: first plots in a) and b)) show quite low values at shallow depths, consistently with seasonal drying. The water content increases sharply to a depth of 40-50cm, then, if the scatter is neglected, it fluctuates around an almost constant value, i.e. the saturated volumetric water content, at greater depths.
With reference to both vegetated and bare conditions, in Fig 4a and 4b respectively, the first test phase within which a constant head (h1) of 15 cm is applied, brings about an increase of ϑ recorded over three hours in the first 40cm, with a maximum value at 30cm. The ϑ variation ($\Delta\vartheta$ on the x-axis) tends to decrease after 40 min of the applied head. Then, the second test phase has been characterized by a constant head (h2) applied of 25cm, which although determined a minor increase of head, the ϑ values rise in the first 10cm correspondingly. However, from the analysis of the water content monitoring data, it appears that the wetting process has not reached the saturated condition, even if it is worth mentioning that the capacitive probe measures the ϑ in a volume surrounding the plastic tube, instead of the well dug for the test, averaging the water content value with soil portion not involved in the wetting process. However, it may be possible that a steady state infiltration rate has not been attained during the test; as such, in order to further investigate the tests performed, numerical back analyses of the Guelph's-induced transient seepage have been planned.

4. Conclusion

The quantitative assessment of the transient seepage processes induced by SVA interaction in the slope needs the hydraulic characterization of the material in the soil cover layer where the gradients determine water flows. Therefore, hydro-mechanical properties of the soil have been investigated in terms of both retention properties and saturated permeability. The present studies focused on site-specific test where a particular type of vegetation was seeded and farmed. Some differences in term of hydro-mechanical properties were found when comparing rooted samples and bare soil ones through both laboratory and in-situ investigations. The WRCs show different Van Genuchten parameters despite having similar grading curves and soil state conditions. The rooted soil, having a RLD higher, has shown saturated permeability values higher by about one order of magnitude if compared to that characterizing the soil in bare conditions. Aware of the limitation of the methods and equipment of the Guelph permeability test, further work would include performing a numerical hydro-mechanical back analysis in a partially saturated and vegetated clayey slope cover to assess the reliability of the saturated hydraulic conductivity values obtained.

Acknowledgments
The research was supported by MIUR PON R&I 2014-2020 program (project MITIGO, ARS01_00964).

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