Proceedings RootS25
3rd International Workshop on Soil-Vegetation-Atmosphere Interaction
Boldrin D, Cecconi M, Cotecchia F, Leung A, Pedone G, Perrini P, Romero E, Tagarelli V, Zdravković L (eds)
ISSN: 3107-300X
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doi: doi.org/10.53243/RootS2025-65

Effects of root systems on the hydraulic behaviour of a clayey slope cover

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ABSTRACT: The interaction between soil, vegetation, and atmosphere (SVA), has become a central topic in geotechnical research, as it governs pore pressure variations within the soil profile and can influence the triggering of weather-induced landslides. These interactions establish a coupled thermo–hydro–mechanical (THM) transient boundary condition at the ground surface, driving exchanges of water, air, and energy within the upper few meters of the soil cover. Consequently, both the THM behaviour of the soil and the characteristics of the vegetation play a key role in controlling slope response under climatic forcing. This study presents a full-scale in-situ experiment where selected *Graminaceae* species were cultivated to investigate the hydraulic behaviour of rooted clayey soil. Laboratory (modified oedometer) and in-situ (Guelph permeameter) tests were performed to evaluate saturated hydraulic conductivities, while water retention properties were determined using the filter paper method. In addition, root length density (RLD) measurements were carried out to quantify root distribution within the tested specimens, and the initial state of the soil was characterised in terms of net void ratio, accounting for the root volume.
Results show that the presence of roots modifies the hydraulic response of the clayey soil cover. Higher RLD is associated with an increase in the saturated hydraulic conductivity (k_{sat}), due to the formation of preferential flow paths and decayed root channels that enhance water transmission. At the same time, the vegetated soil exhibits a reduced water retention capacity compared with bare conditions, reflecting the combined effects of macropore connectivity and reduced matrix suction.

Keywords: Rooted soil; Hydraulic conductivity function; Guelph permeameter; Root length density; net void ratio

1 INTRODUCTION

Recent advances in geotechnical research have highlighted the crucial role of soil–vegetation–atmosphere (SVA) interaction in governing the near-surface conditions of geotechnical systems (Cecconi et al., 2025). In natural slopes, SVA processes drive temporal variations in pore water pressure, even within low-permeability clayey soils, thereby influencing the onset and evolution of rainfall-induced landslides (Cotecchia et al., 2019).

Based on both phenomenological evidence and numerical analyses, it has been shown that landslide activity in clayey slopes can be recurrently triggered by SVA interactions occurring within the uppermost soil layers (Cotecchia et al., 2019). These processes may induce transient seepage reaching several meters below the surface, leading to significant pore pressure fluctuations and temporal changes in available shear strength, which ultimately affect the slope equilibrium. Such interactions have been recognised as a key triggering factor for both shallow slides and the seasonal acceleration of deep-seated landslides in clayey deposits (Tagarelli & Cotecchia, 2025).

In this respect, the determination of the saturated hydraulic conductivity (k_{sat}) and the soil water retention curve (SWRC) under both rooted and bare conditions provides essential input parameters for numerical analyses aimed at simulating transient seepage and pore pressure response (e.g., Stasi et al., 2024). Such measurements are fundamental for developing accurate, site-specific predictive models, which are in turn necessary to design reliable early warning systems (Tagarelli & Cotecchia, 2025).

These hydraulic constitutive properties are strongly influenced by soil type, vegetation characteristics, and climatic regime, which together control the magnitude and temporal evolution of SVA processes (Smets et al., 2020; Stasi, 2024). As a result, the coupled hydro-mechanical behaviour of vegetated soils is highly site-specific and difficult to generalize. This complexity highlights the importance of experimental studies aimed at quantifying the local response of the soil–vegetation system and at providing reliable input parameters for model calibration.

The influence of roots on the saturated hydraulic conductivity (k_{sat}) has been reported with contrasting outcomes in the literature. Some authors observed that root growth enhances macroporosity and preferential flow, leading to increased k_{sat} values in fine-grained soils (Ghestem et al., 2011), while others found that dense root networks or biopores partially clogged by organic matter can reduce overall permeability (Leung et al., 2018). Similar variability has been reported for the soil water retention curve (SWRC), which may

exhibit either a reduction in air-entry value and water-holding capacity due to increased macropores, or an opposite effect when root residues and organic matter increase microporosity (e.g., Stasi et al., 2025). Moreover, discrepancies between laboratory-determined and in-situ values of k_{sat} are widely recognized in the literature (Tagarelli et al, 2023; Stasi, 2024). Such differences arise from the different volumes involved in the seepage process and from the scale-dependent heterogeneity of natural soils. In rooted soils, this discrepancy may become even more pronounced due to the spatial variability of root density and the resulting flow paths (Leung et al., 2018; Vergani & Graf, 2016; Stasi et al., 2024).

Within this framework, the present study contributes to improve the modelling of SVA-induced processes by experimentally characterising the main hydraulic constitutive relationships of rooted clayey soils. Field and laboratory investigations were conducted on the Pisciolo landslide (southern Apennines, Italy; Cotecchia et al., 2019), comparing bare, B, and vegetated, V, soils, where selected Gramineae species were provided by PratiArmati s.r.l. (Tagarelli & Cotecchia, 2022).

2 MATERIALS AND METHODS

Extensive field and laboratory investigations have been conducted in recent years to characterise the geo-hydro-mechanical behaviour of the clayey soils (clay fraction 20–60%) forming the Pisciolo slope (Cotecchia et al., 2019; Stasi, 2024). Generally, the soil is a clay slightly gravelly, sandy, and silty (according to AGI 1994) with a plasticity index ranging between 30-48% and an activity of 0.72-1.1 (Stasi, 2024).

Hydraulic characterisation of the clayey topsoil, both vegetated, V, and bare, B (Figure 1), involved determining the saturated permeability, k_{sat}, through field and laboratory testing.

To this aim, a cylindrical soil sampler was used in situ to obtain undisturbed specimens. Samples with a diameter of 56 mm and a height of 20 mm were then prepared for constant head permeability tests in a modified permeameter (Bottiglieri et al., 2012). The device allows for the direct measurement of k_{sat} of the soil specimens under oedometer stress-strain conditions. In all tests, upward vertical seepage was applied by increasing the base pore water pressure to values between 5 kPa and 20 kPa, while maintaining free drainage conditions at the top of the specimen. This setup generated a small hydraulic gradient through the specimen, thereby preventing excessive heterogeneity in the effective stress in the soil sample.

Field k_{sat} values were measured with the Guelph permeameter (Soilmoisture Equipment Corp., 2008) during two different tests, in May 2021 and March 2022, following the procedure adopting the single-head solution of Elrick et al. (1989). Tests were performed under constant heads of 15 cm or 25 cm for durations of 2–3 hours. During each test, undisturbed samples were also collected for laboratory determination of soil state parameters, serving as input for a numerical back-analysis that has been carried out to back-analyse the values of the saturated permeability (Tagarelli et al., 2024). The Guelph-induced transient seepage was simulated using fully coupled hydro-mechanical analyses in PLAXIS 2D, incorporating the Mualem–van Genuchten hydraulic model and the Mohr–Coulomb constitutive law, as detailed by Tagarelli et al. (2023).

The partially saturated behaviour was investigated through water retention tests (in wetting or in drying), measuring suction with the filter paper method, following Pedone et al. (2022). Root density was quantified by separating roots post-testing, followed by digital image analysis using RhizoVision Explorer (Seethepalli et al., 2021) to compute root length density (RLD) (Stasi, 2024). The net void ratio, e_{net}, was computed as:

$$e_{net} = \frac{V_{tot} - V_s - V_r}{V_s + V_r} \quad (1)$$

where V_r is the volume of the roots, V_s is the volume of the soil, and V_{tot} is the total volume.

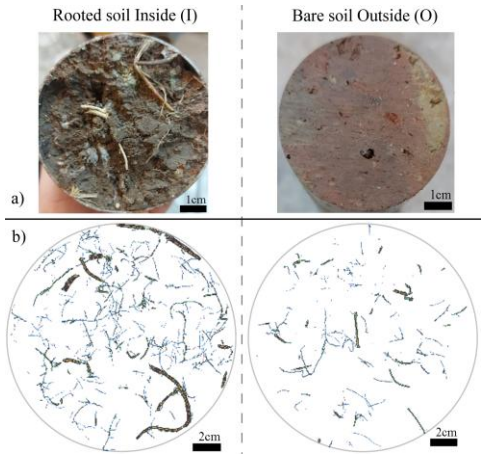


Figure 1. Photos of undisturbed samples retrieved in May 2021 (a) and corresponding scanned root image (b), V sample on the left-hand side and B sample on right-hand side

3 DISCUSSION OF THE TEST RESULTS

Laboratory water retention data are shown in Figure 2 in term of degree of saturation, S_r, vs suction, s (Figure 2a) and specific volume (derived from e_{net}), v, vs suction (Figure 2b). The data demonstrate that root presence slightly reduced the air-entry value and steepened the retention curve, indicating a lower retention capacity in rooted soils (V). These results agree with previous findings (Lu et al., 2020), suggesting that root growth modifies the mesostructure by aggregating fine particles and increasing macropores (Stasi et al., 2024).

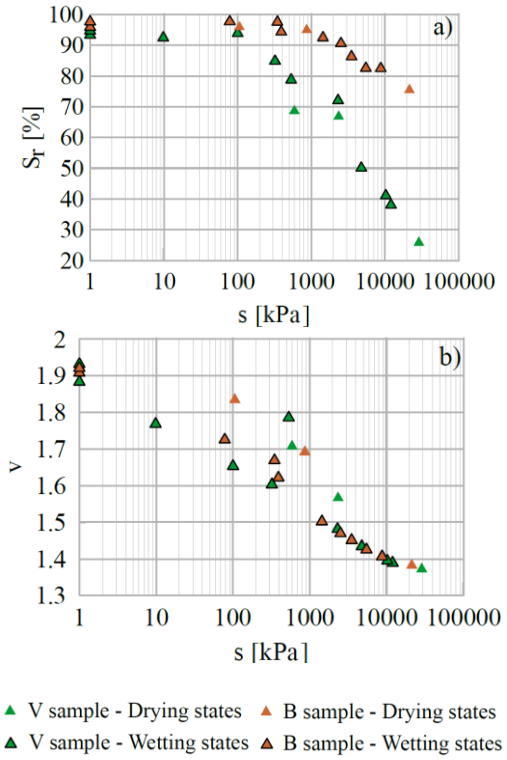


Figure 2. Soil retention states in terms of a) S_r-s and b) v-s for V and B specimens along both drying and wetting paths

Figure 3 compares the values of saturated hydraulic conductivity obtained through permeameter tests and in-situ Guelph measurements for both V and B soil areas. Data are presented for different sampling locations relative to the vegetation: directly at the plant base (V_1-0 and V_2-0) and at 30 cm in plane distance (V_1-30). Figure 3a shows the variation of e_{net} with depth for all tested specimens, while Figure 3b presents the RLD profiles. Figures 3c and 3d illustrate how e_{net} and k_{sat} vary in relation to RLD. From Figures 3a and 3b, it appears that the net void ratio is not strongly related to depth. Only a slight decrease in e_{net} is observed in the V specimens compared with the B specimens. This occurs despite the presence of roots, as shown by the RLD profiles in Figure 3b.

In situ k_{sat} values, computed via the Guelph method (Elrick et al., 1989), ranged between 4.5×10^{-9} m/s and 3.9×10^{-9} m/s in the bare area and between 5.9×10^{-8} m/s and 7.4×10^{-8} m/s in the vegetated area. Numerical back-analyses using PLAXIS 2D produced lower k_{sat} estimates—3×10^{-9} m/s and 1.3×10^{-9} m/s for V tests, and 6×10^{-10} m/s and 3×10^{-10} m/s for B tests. This highlights that the analytical solutions may tend to overestimate the permeability (Tagarelli et al., 2023).

In contrast, laboratory permeameter tests result in a k_{sat} value of 1.8E-09 m/s measured on a V specimen collected at a depth of 5 cm below ground level; whereas the minimum value of 4.2E-11 m/s was measured at a depth of 40 cm on bare soil and 5.4E-11 m/s at a depth of 50 cm on vegetated soil.

Root density analyses revealed values of 0.2–16 cm*cm^{-3} for V samples and 0–0.9 cm*cm^{-3} for B samples, typical of grass species (Lu et al., 2020). Image analysis confirmed that most roots were 0.5–1 mm in diameter, with thicker roots (1–4 mm) more common in the first 10 cm.

The k_{sat} values measured in the field are consistently higher than those determined in the laboratory, in agreement with previous observations on structured and rooted soils (Ghestem et al., 2011; Leung et al., 2018; Vergani & Graf, 2016). This confirms that field-scale permeability is enhanced by the structural and biological heterogeneity of the soil. This divergence reflects the influence of scale effects and root density on the representative element volume (REV). High RLD values increase the REV due to enhanced heterogeneity (Stasi, 2024). Consequently, standard laboratory specimen sizes (56 × 20 mm) may inadequately capture the field-scale hydraulic behaviour of root–soil systems.

A distinct spatial trend is observed around the vegetation. For V_1-0 and V_2-0, where the RLD is highest, k_{sat} reaches its maximum values. At V_1-30, both k_{sat} and RLD decrease. Despite this reduction in RLD being accompanied by a slight increase in the e_{net}, the hydraulic conductivity still diminishes.

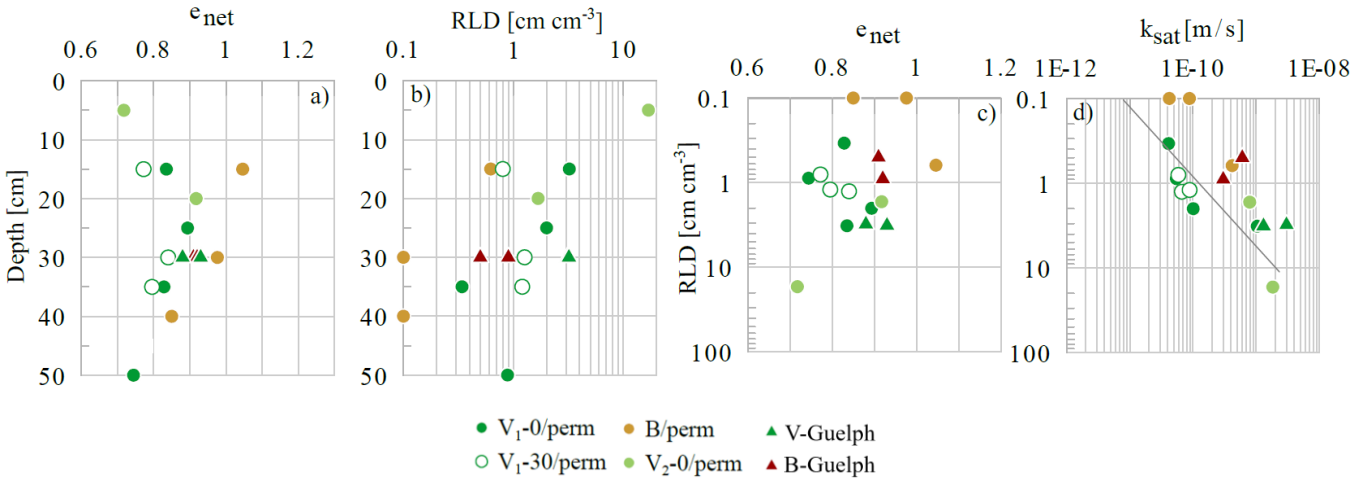


Figure 3. Results of k_{sat} determinations in the laboratory by means of a modified permeameter and in the field with a Guelph permeameter, plotted against depth and the corresponding values of e_{net}, and RLD

This behaviour suggests that the presence of roots may enhance permeability not by increasing porosity (as e_{net} is similar, or even lower, in V specimens compared with B ones; see Figure 3c), but rather by creating preferential flow paths (biopores and decayed root channels) that form a connected and hydraulically active network. These macropores enable water to bypass the fine soil matrix, causing higher infiltration rates even when the e_{net} is lower. Similar trends have been reported in the literature, highlighting the role of decayed roots and biochannels in increasing the permeability of fine-grained soils (Ghestem et al., 2011; Leung et al., 2018).

Finally, the data show a clear positive correlation between k_{sat} and RLD (black line in Figure 3d).

4 CONCLUSIONS

This study contributes to the understanding of how root systems influence the hydro-mechanical behaviour of rooted soils. Despite the limited dataset, the findings suggest that roots affect both the SWRC and the k_{sat}. Rooted soils exhibit lower water retention than bare soils, with reduced air-entry values and steeper SWRC slopes. Roots also increase soil permeability, as consistently observed across in-situ and laboratory.

Further research should refine the definition of REV for soil–root systems and investigate biochemical interactions between roots and pore water that may further influence hydro-mechanical behaviour.

5 ACKNOWLEDGEMENTS

The authors acknowledge the project PNRR, MISURA M4_C2_1.4, National Centre for HPC, Big Data and Quantum Computing (CN_00000013).

6 REFERENCES

Bottiglieri, O., Cafaro, F., Cotecchia, F. 2012. Estimating the retention curve of a compacted soil through different testing and interpretation methods. *Unsaturated Soils: Research and Applications* **1**, 47–54.

Cecconi, M., Tagarelli, V., Cotecchia, F., Pane, V., Anselmucci, F., Bertolini, I., Biondi, G., Boldrin, D., Capobianco, V., Cardile, G., Cuomo, S., De Vita, P., Fraccica, A., Meijer, G., Pagano, L., Pirone, M., Schwarz, M., Tarantino, A., Vaunat, J.,Yildiz, A. 2025. Soil–vegetation–atmosphere interaction for engineering applications: recent multi-scale and multi-disciplinary insights, *Geomechanics for Energy and the Environment* **43**, 100723.

Cotecchia, F., Tagarelli, V., Pedone, G., Ruggieri, G., Guglielmi, S., Santaloia, F. 2019. Analysis of climate-driven processes in clayey slopes for early warning system design, *Géotechnique* **172**(6), 465–480.

Elrick, D.E., Reynolds, W.D., Tan, K.A. 1989. Hydraulic conductivity measurements in the unsaturated zone using improved well analyses, *Groundwater Monitoring & Remediation* **9**(3), 184–193.

Ghestem, M., Sidle, R.C., Stokes, A. 2011. The influence of plant root systems on subsurface flow: implications for slope stability, *Bioscience* **61**(11), 869–879.

Leung, A.K., Garg, A., Ng, C.W.W., Hau, B.C.H. 2018. Effects of plant roots on soil–water retention and induced suction in vegetated soil, *Engineering Geology* **233**, 132–148.

Lu, J., Zhang, Q., Werner, A.D., Li, Y., Jiang, S., Tan, Z. 2020. Root-induced changes of soil hydraulic properties – a review, *Journal of Hydrology* **589**, 125203.

Pedone, G., Cotecchia, F., Tagarelli, V., Bottiglieri, O. 2022. An investigation into the water retention behaviour of an unsaturated natural fissured clay, *Applied Sciences* **12**(19), 9533.

Seethepalli, A., Dhakal, K., Griffiths, M., Guo, H., Freschet, G.T., York, L.M. 2021. RhizoVision Explorer: open-source software for root image analysis and measurement standardization, *AoB Plants* **13**(6).

Smets, T., Poesen, J., Knapen, A. 2020. Impact of vegetation on soil hydrology and erosion: a review, *Progress in Physical Geography* **44**(4), 565–595.

Stasi, N. 2024. *Experimental and numerical study of soil–vegetation–atmosphere interaction for the design of nature-based solutions in landslide risk mitigation*. PhD Thesis, University of Bari – Politecnico di Bari.

Stasi, N., Tagarelli, V., Cafaro, F. and Cotecchia, F. 2024. The Impact of a Wildfire on a Vegetated Topsoil: Field Monitoring and Numerical Modeling. *International Conference on Sustainable Development in Civil, Urban and Transportation Engineering,* 235-243. Springer Nature Singapore, Singapore.

Stasi, N., Tagarelli, V., Cafaro, F., Cotecchia, F. 2024. On the Wildfire-Induced changes in the properties of a vegetated clayey slope cover, *ISC2024* **202**(4.276). https://doi.org/10.23967/isc

Stasi, N., Tagarelli, V., Cafaro, F., Cotecchia, F. 2025. On the use of a water potential probe for suction and temperature measurements in unsaturated natural clayey soil, *Applied Sciences* **15**(6), 3021.

Tagarelli, V., Cotecchia, F. 2022. Preliminary field data of selected deep-rooted vegetation effects on the slope–vegetation–atmosphere interaction: results from an in-situ test, *Italian Geotechnical Journal* **56**(1), 62–83. https://doi.org/10.19199/2022.1.0557-1405.062

Tagarelli, V., Stasi, N., Cotecchia, F. 2023. Numerical back-analysis of in-situ constant head tests in partially saturated soil cover to determine the permeability function. *National Conference of the Researchers of Geotechnical Engineering*, 275–282. Cham: Springer Nature Switzerland.

Tagarelli, V., Stasi, N., Cotecchia, F., Cafaro, F. 2024. Root-induced changes in the hydraulic properties of a fine slope cover, *E3S Web of Conferences* **544**, 16002. EDP Sciences.

Tagarelli, V., Cotecchia, F. 2025. Weather-induced landslide activity in clayey slopes: modeling for the design of site-scale early warning systems, *Journal of Geotechnical and Geoenvironmental Engineering* **151**(9), 04025092.

Vergani, C., Graf, F. 2016. Soil permeability, aggregate stability and root growth: a critical review, *Catena* **142**, 43–57.