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Soil-vegetation-atmosphere interaction for engineering applications: Recent multi-scale and multi-disciplinary insights

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ABSTRACT

The paper presents some of both recent and previous outcomes on soil-vegetation-atmosphere mechanisms and processes. Contributions from several authors across different scientific fields, each focusing on specific aspects of soil and plant behaviour under variable climatic conditions, highlight the urgency of multi- and inter-disciplinarily research aimed at the investigation, analysis, and modelling of soil-vegetation-atmosphere (SVA) interaction. The paper focuses on different aspects of such interaction, which plays the crucial role of a thermo-hydro-mechanical boundary condition acting at the ground surface and controlling the transient behaviour of every geotechnical system. Some specific remarks and novel aspects of such interaction, analysed at increasing levels of complexity, are depicted in the paper through a multi-disciplinary point of view and according to a multi-scale methodology.

1. Introduction

Vegetation certainly plays a crucial role in the context of disaster risk reduction and sustainable management of ecosystems. As noted in the literature (e.g.,[8,43]), integrating disaster risk reduction through both structural and non-structural measures into natural resource management has been identified as a key activity. This approach aligns with strategies for reducing disaster risk and adapting to climate change, as outlined in recent international frameworks, such as the Hyogo Framework for Action (2005–2015) and the Cancun Adaptation Framework (2010). They both recognized the need to enhance climate change related disaster risk reduction strategies through economic diversification and sustainable management of natural resources.[206] These targets have also been called for by the Sendai Framework for Disaster Risk Reduction 2015–2030[207] which promotes the implementation of ecosystem-based approaches to stimulate the resilience of the systems and to reduce the hazard associated with natural

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List of symbols and acronyms

AEV	Air entry value
BVP	Boundary value problem
CC	Consequence classes
COV	Coefficient of variation
D_{50}	Median grain size
DIC	Digital image correlation
EC0	Euro Code 0
EC7	Euro Code 7
FS	Factor of Safety
H	Hydraulic
HM	Hydro-mechanic
h_r	Root depth
IAT	Image analyses techniques
k_{sat}	Saturated hydraulic conductivity
LAI	Leaf area index
M	Mechanical
M_{root}	Root mass
NBS	Nature-based solutions
NPK	Nitrogen, Phosphorus and Potassium
n_v	van Genuchten parameter
P_f	Slope probability of failure
P_g	Pressure of the gas
P_l	Pressure of the liquid
PIV	Particle image velocity
Pl	Pressure of the liquid
PSD	Pore size distribution
RAI	Root area index
RAR	Root area ratio
RBD	Reliability-based design
REVs	Representative elementary volume
RLD	Root length density
RWU	Root water uptake
s	Suction
SI	Stability index
SVA	Soil-vegetation-atmosphere
SWRC	Soil water retention curve
T	Temperature
TH	Thermo-hydraulic
THM	Thermo-hydro-mechanical
u	Displacement vector
ULS	Ultimate limit state
VWC	Volumetric water content
α	Slope inclination
β	Reliability index
$\Delta\tau_r$	Roots-induced shear strength increase
θ_r	Residual volumetric water content
θ_s	Saturated volumetric water content
ϕ'	Soil friction angle
Φ	Cumulative distribution function
σ_t	Tensile root strength
k_{unsat}	Partial saturated hydraulic conductivity
$\lambda(T)$	Thermal conductivity coefficient
α_{lin}	Linear expansion coefficient
α_{vol}	Volumetric expansion coefficient
χ	Bishop effective stress parameter

phenomena and the corresponding vulnerability of exposed elements to disaster risk.[205] In addition, the sustainable development goal (SDG) target 15.3 on land degradation was identified to recognize the importance of soil preservation.[97,208] Within Europe, forests cover about 39 % (160 million hectares) of the total land area, and despite a slowdown in deforestation rates, over 420 million ha of forest have been lost since the 90's, with an annual loss of 10 million ha (Eurostat, 2024). Reducing deforestation and forest degradation, as well as restoring forests, represent critical issues to meet the 2030 global goals. Moreover, in many countries, protection forests are defined as an important part of the integrated risk management due to landslide hazards and are actively managed for such purpose.[199]

In the last two decades, the scientific research has aimed at investigating the beneficial impact of vegetation on slope failure mitigation, for either shallow or deep failures, making significant steps forward. The relevant number of variables and conditions playing a non-negligible role in the influence of vegetation on slope stability, makes this subject very complex and, consequently, makes it difficult to reach solutions whose efficacy may be guaranteed in the long term for varying soil and weather conditions. The geologic, hydrological, topographic conditions, the physical soil properties and initial soil state (e.g. the soil water content, degree of saturation and suction), the soil mechanical properties, the plant/tree features (type, composition, root system, etc.), as well as the rainfall and evapotranspiration scenarios, canopy interception, earthquake-induced ground motions etc., are only some of the factors/processes that need to be accounted for in the assessment of the Soil-Vegetation-Atmosphere (*SVA*) interaction. In turn, the assessment of the *SVA* interaction often represents the background of the design of a sustainable and efficient Nature-Based Solution (*NBS*) of use for mitigation purposes. Therefore, the use of *NBS* to make stability measures sustainable requires the investigation of *SVA* interaction through experimental, analytical and numerical studies. As with most geotechnical applications, it is beneficial to study the behaviour of vegetated slopes at different scales. Initially, reduced laboratory and physical model scales should be considered, where factors and processes can be controlled, before attempting to interpret full scale behaviour pertaining to site conditions.

However, the issues tackled in this paper are expected to contribute not only to the understanding of the behaviour of both natural and cut slopes, when interacting with the vegetation and the atmosphere, but also to a broader range of geotechnical systems. Indeed, with the exception of peculiar applications, like deep underground geotechnical structures (e.g., tunnels), many geotechnical systems may benefit from an improved interpretation of the thermo-hydro-mechanical (*THM*) processes driven by soil-vegetation-atmosphere (*SVA*) interactions.

This is because, a geotechnical system including a physical domain composed of soil/rock, water and air, and generally interacting with a geotechnical structure (e.g., foundations, retaining structure, embankment, etc.), is influenced by mechanical, hydraulic, thermal, and, when relevant, chemical or biological processes. Within its spatial extent, interactions occur between the soil and external factors such as atmospheric conditions, groundwater dynamics, and structural loads (in both static/seismic conditions). These interactions contribute to define the stress-strain state of the soil and hence, to control the behaviour of the whole system. In this respect, the boundaries of the geotechnical system assume high relevance in determining the *THM* state of the soil (i.e., stress distribution, strain field, water flows, infiltration, and pore pressure variations, as well as thermal effects) over time. Typically, when the ground surface is among the boundaries of the geotechnical system, exchanges of energy and water with the atmosphere take place and should be modelled. Hence, the SVA interaction plays a fundamental role in modifying subsurface conditions since rainfall, evapotranspiration, and temperature variations drive changes in soil moisture and suction, which in turn influence strength, stiffness, and overall stability.

Understanding and accurately modelling *SVA* interactions is therefore essential for assessing and predicting the evolution of these systems under both natural and anthropogenic actions.

This paper presents an attempt to integrate specialized knowledge contributions about *SVA* interaction, coming from different scientific expertise, which span from geotechnical engineering, to agronomy, to forestry science. In this perspective, the soil-vegetation-atmosphere mechanisms and processes are discussed. Given the diversity of fields involved, the novelty of the paper stands primarily in combining knowledge on the main thermo-hydro-mechanical processes controlling *SVA* interaction across these disciplines. The aim is to provide our best comprehensive, expert and up-to-date description of these processes, i.e. by examining them from different perspectives and at different scales.

2. The contribution of inter-disciplinary and multi-scale studies in the modelling of the *SVA* interaction as a boundary condition of geotechnical systems

The soil-vegetation-atmosphere (*SVA*) interaction results from the combination of several coupled processes and represents a thermo-hydro-mechanical boundary condition exerting control over the transient behaviour of many geotechnical systems. From the outset, let it be clarified that in this paper, the term "vegetation" refers to an assembly of plants (herbaceous, shrubs or tree plants), irrespective of their botanical species, incorporating both the above-ground portion and the embedded roots.

2.1. Processes in SVA interaction: nature, complexity and coupling

The SVA interaction encompasses a multitude of processes, each characterised by a distinct nature, such as hydraulic, mechanical, thermal, biological, chemical, and physiological. A multi-disciplinary approach is imperative to understand and effectively address the complexities associated with the *SVA* interaction, requiring synergy and integration across diverse scientific fields through a holistic perspective. Furthermore, in depicting the complexities within the *SVA* interaction, it should be considered that the analysis of these processes depends both on the time scales and the selected Representative Elementary Volumes (*REVs*), which should be probably larger than usually considered in non-vegetated soils. This aspect is essential for the understanding each specific process within the SVA interaction. The scale of these processes is also directly connected to the scale of the Boundary Value Problem (*BVP*) under consideration, thus implying a hierarchical approach to tackle geotechnical problems. Scientific literature extensively documents the multifaceted nature of the SVA interaction,[130,235,78,87] providing valuable insights into the coupling of the different processes involved. However, such complexity prompts the development of simplified but equivalent representations that facilitate modelling when applied to practice and engineering applications. This equivalent model serves as a “surrogate” for the more intricate and detailed SVA models (among the others,[154,134,9]), streamlining the analysis of geotechnical systems while retaining the key features that influence transient behaviours. Elia & co-authors[62] explore the developments and some applications of such equivalents, showcasing the utility of these simplified models in capturing the essential aspects of the SVA interaction in the engineering practice.

In the intricate interplay between vegetation and soil mechanics, understanding the mechanisms through which vegetation contributes to soil mechanical reinforcement is crucial to understand the evolving processes within the soil-root composite. Several factors of different nature influence the whole behaviour of this composite, among which the root system type, its growth phases, and the soil state are the most relevant. Traditionally, the primary effect vegetation may exert on the rooted soil performance is considered by assuming the roots as natural fibres which improve the soil shear stiffness and strength. In this conception, the type of root system the vegetation develops assumes a central role. Different plant species deploy distinct root architectures, ranging from tap roots to fibrous root systems (among others,[186]), each imparting peculiar mechanical characteristics to the soil-root composite.[18] The specific biomechanical properties of roots, including their diameter, tensile strength, spatial distribution and adhesion of the roots to the soil matrix (i.e., root pull-out), play a pivotal role in determining the overall mechanical behaviour of the composite system and affect the stability condition of the shallowest soil portion of slopes, mitigating the occurrence of slip movements also in presence of extreme meteorological events and/or large earthquake-induced ground motions.[111,173,241,31,37,69]

Furthermore, the biological life cycle of the vegetation introduces the time factor when considering the interpretation of the sole soil-root interaction, not considering the transient action of the atmospheric action. Indeed, as plants experience their life cycle, alterations in root morphology, density, and strength occur, influencing the mechanical properties of the surrounding soil. Early stages of growth, characterised by vigorous root expansion and establishment, contribute to a distinctive set of soil-root composite properties compared to later stages when root systems may become more stabilising and maturation-oriented.[12,67] It is crucial to note that also the state of the root system, encompassing factors such as root vitality and health, root moisture, cellulose content and the degree of root-soil adherence, profoundly control the mechanical behaviour of the soil-root composite. Root vitality, for instance, influences the degree of soil compaction and root penetration, thereby impacting soil shear strength and cohesion.[186] The physical interlocking between roots and soil particles, mediated by factors like root morphology, root exudates and mycorrhizal associations, further contributes to the mechanical reinforcement of the composite system.[27,28,172]

Moreover, soil movements either artificial or natural, e.g., shallow slips or erosion may produce widespread vegetation damage affecting roots mortality and their subsequent development after the event. Accordingly, impacts on the hydraulic and mechanical properties of the soil-root composite and, thus, on the whole SVA interaction processes, are apparent and for instance when dealing with post-seismic landslides susceptibility, this may also affect future performance of vegetated slopes arising in the stroked area (e.g.,[2,47,64,230]).

Although the SVA interaction represents a strongly coupled boundary condition, the vegetation’s root system acts on a finite volume of the soil-root composite, also exerting a mutual action on the rooted soil’s physical, hydraulic, thermal and mechanical properties.[234,79,89] This mutual interaction is dependent on the type and state of both the soil and the vegetation.[5,42,131] This emphasises the transient and heterogeneous nature of the soil-vegetation interaction, with roots acting as integral components that adapt and respond to the surrounding soil environment and vice versa.[13] Scientific literature, as evidenced by studies from Stokes,[185] Boldrin et al.,[19] Schwarz et al.,[174] and others, provides useful insights into the biomechanical aspects of root-soil interactions.

As mentioned above, an essential issue to be addressed for an accurate phenomenological description of a geotechnical system for which vegetation may play a significant role is the consideration of full thermo-hydro-mechanical (*THM*) behaviour and impact. Otherwise, specific energy-driven processes within the *SVA* interaction, such as the desiccation crack formation and the water evaporation from the soil cover, cannot be properly accounted for and simulated eventually. In particular, the thermal properties of the soil-root composite result from the thermal conductivity and heat capacity of both soil and roots, with the latter acting as conduits for heat transfer.[101,146,75] Similarly, the hydraulic behaviour is linked to root water uptake, soil moisture “dynamics”, and the interplay of capillary and osmotic processes.[45,171,120,227] The impact of vegetation extends beyond just modifying the root-soil properties, and, indeed, the vegetation concurs also to determine the transient thermal and hydraulic boundary condition at the ground surface. This transient action is driven by the atmospheric forcing actions, encompassing factors such as air temperature, humidity, and solar radiation. The vegetation, through its root system, influences soil

Table 1
Outline of the most relevant mechanical, hydraulic and thermal properties and the corresponding parameters to be provided aimed at carrying out analyses at different levels of complexity.

	a		b	c	d	e	f
	Coupled Mechanisms / Processes (interaction levels)		**Properties / features**	**Description**	**Input for the analysis/modelling**	**Measuring techniques**	**Relevant studies**
1	Mechanical (M)	• Strength • Stiffness	Root type	Root system typology	Tap root system, Fibrous root system	Field survey Literature data	Wilson[219]; Aktinson[10]
			Geometry Root system	Root system geometrical arrangement	RAR (depth)	Field survey (direct or indirect)	Comino and Druetta[40]; Schwarz et al.[172]; Mahannopkul and Jotisankasa[123]; Świtała et al.[188]
			Root state	Roots biological state	Alive/Dead Lignin content	Field survey (direct or indirect)	Mahannopkul and Jotisankasa[123]; Zhang et al.[240]
			Root strength	Tensile root strength	σ_t Elastic moduli	Laboratory testing In situ testing	Wu et al.[225]; Pallewattha et al.[148]; Tan et al.[197]
			Root-soil composite strength	Roots-induced shear strength increase	$\Delta\tau_r$ (depth)	Laboratory testing In situ testing	De Baets et al.[52]; Schwarz et al.[175,173]; Cislaghi et al.[34]; Fraccica et al.[69,70]; Cuomo et al.[48]
2	Hydraulical (H)	• Retention property • Hydraulic conductivity	Hydraulic conductivity	Saturated permeability coefficient	k_{sat}	Laboratory testing In situ testing Numerical Back-analysis	Jotisankasa et al.[95]; Vergani and Graf[212]; Fraccica et al.[71]
				Hydraulic conductivity function (HCF)	$k_{unsat} = f(s)$	Laboratory testing In situ testing Numerical Back-analysis	Lu et al.[120]; Tagarelli et al.[195]
			Soil-water-roots retention property	Soil-water retention curve (SWRC)	$s = f(\vartheta)$	Laboratory testing In situ testing Numerical Back-analysis	Ng et al.[136]; Lu et al.[120]; Capobianco et al.[25]; Dias et al.[57]; Leung et al.[112]; Pedone et al.[149]; Fraccica et al.[72,71]; Stasi et al.[182]; Tagarelli et al.[196]
3	Thermal (T)	• Energy diffusion	Thermal conductivity	Thermal conductivity coefficient	$\lambda(T)$	Laboratory testing Numerical Back-analysis	Wierenga et al.[218]; Blanco-Canqui et al.[16]; Dong et al.[58]
			Thermal expansion	Linear, volumetric coefficient	α_{lin}, α_{vol}	Laboratory testing Literature data	Loria et al.[118]

temperature profiles and moisture content in the soil, thereby impacting the thermal and hydraulic conditions experienced by the soil-root composite. Several scientific works[4,46,99,117,124,160,170,193] offer significant insights into the complexities of thermal and hydraulic processes within the SVA interaction. These studies further emphasise the manifold nature of this interaction and corroborate the necessity of adopting *THM* analyses for the diagnosis and the prediction to understand the whole process involving a geotechnical system comprehensively.

Moreover, the impact of vegetation within the SVA interaction does not only concern the thermo-hydro-mechanical balances but also influences the chemistry of the soil pore fluid by selectively up-taking or releasing substances, which, in turn, may affect soil compressibility, strength and hydraulic properties.[94] In most cases, the chemical processes occurring within the soil-root composite, while the root system is both developing and acting, are disregarded since their impact may often be negligible.[93,214]

2.2. A framework for future research on the SVA interaction

With these premises in mind, some of the latest developments in the study of *SVA* interaction are presented and discussed in this paper to propose a common background that can be considered useful and possibly give rise to new insights for further research within this complex topic. Indeed, in the following sections, the *SVA* interaction will be tackled by discussing the strengths and limitations of the approaches corresponding to three increasing levels of complexity, indicated in the Table 1: i) basic level: soil-roots interaction; ii) intermediate level: soil-roots-water interaction; iii) advanced level of complexity: soil-vegetation-atmosphere interaction.

In the following, innovative and advanced laboratory techniques will be recalled when presenting experimental results. Most of the experimental studies presented here are based on different scales and types of investigation, spanning from laboratory microstructural analyses, e.g., employing X-ray tomography and digital Image Correlation, through laboratory testing of larger rooted soil specimens, e.g., direct shear and large triaxial tests, to measurements of the thermo-hydro-mechanical behaviour of the rooted soil logged in the field.

All the evidence presented in the following sections will not only help establish a shared background for scientific research on SVA interaction but will also have practical applications by defining the

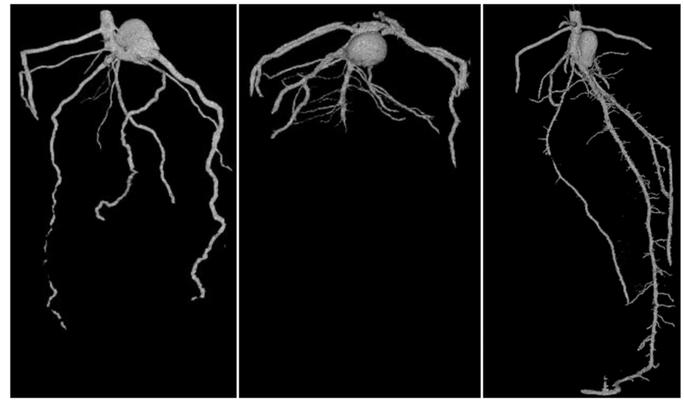

Fig. 2. Root system architecture of a young Zea L. Maize seedling - 8 days old - plant growth in a): Hostun Sand HN31 with Relative density of 30 %; b): Hostun Sand HN31 with relative density of 80 %; c): Hostun Sand HN1.5–2 with relative density of 30 % (modified from Anselmucci at al.[6]).

requirements for selecting an appropriate level of complexity for a given study. In this regard, Table 1 is intended to be both useful and practically applicable, as it provides a structured overview of the most relevant mechanical, hydraulic, and thermal processes to be considered when performing analyses at different levels of coupling. Specifically, Table 1 lists, for each interaction level—mechanical (M, row 1), hydraulical (H, row 2), and thermal (T, row 3)—the key processes and mechanisms involved (column a). For each of these, the table also presents the relevant properties of the rooted soil or characteristics of the root system (column b), along with a brief description (column c) and the corresponding parameters used to quantify these properties or features (column d). These parameters should be regarded as the input data required for analyses of varying complexity (M, HM, or THM). Additionally, Table 1 includes commonly adopted techniques and methods for determining each parameter (column e), as well as selected references from the literature that are considered particularly relevant and informative (column f).

Each section of Table 1 corresponds to one of the aforementioned complexity levels and is useful in supporting the concepts described in

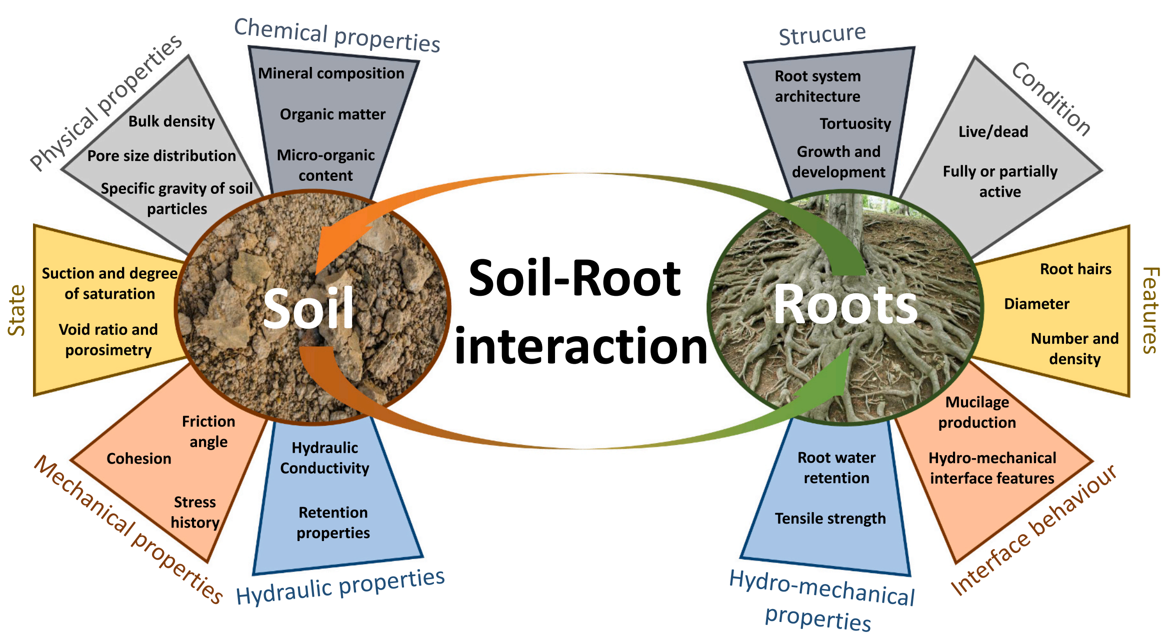

Fig. 1. Multiple interactions between roots and hosting soil (Modified from Loades et al.[115]).

the following Sections, from 3 to 5.

3. Soil-roots (M) interaction: basic level of complexity

It has been widely acknowledged that when studying roots' effects on soil behaviour, the way the soil itself can influence the roots' features cannot be disregarded, as effectively shown by Loades et al.[115] Fig. 1 shows briefly all the mechanisms involved in the interaction process between the soil and the roots, highlighting how difficult the whole soil-root system is to characterise. It is clarified that indeed, chemical, physical, mechanical and hydraulic properties of the soil, together with its state, play a non-negligible role in the interaction with the roots; on the other hand, the hydro-mechanical properties as well as the structure, condition, features and interface behaviour of the root system impact on the overall behaviour of the soil-root composite. As consequence, deepening the understanding of the feedback loops between roots and soils is crucial to identify the initial soil characteristics (i.e. physical properties and chemical composition) that affect vegetation development and thus, for example, help maximise the mechanical effectiveness of roots in engineering applications (M–interaction). In this respect, Stokes et al.[186] provided a comprehensive overview of roots' features (Table 1) of some interest for geotechnical purposes.

As an example of the effect that different soil states and types may have on the overall soil-root composite, Anselmucci et al.[6] illustrated how a single plant, with identical genetics and age, can exhibit markedly different root system development solely due to variations in soil grain size distribution and relative density (Fig. 2). It was found that greater soil density results in a shallower root system. Indeed, the initial soil state, in terms of microstructural state, initial relative density/voids ratio, and grain size distribution, affects the root development and the ability to displace solid grains, with indirect consequences on root orientation, lengths and diameters.[136,41,49]

In this respect, it was generally believed that the roots development in the soil matrix leads to an increased soil porosity. Although Dexter's model[54] partially aligns with this observation, findings by Helliwell et al.,[86] Koebernick et al.,[102] and Lucas et al.[121] have revealed nuances. These researchers identified a small zone of increased soil porosity near the root periphery, primarily attributed to geometric effects resulting from the steric exclusion of soil particles near the root surface. No consistent trend emerged at greater distances from the root, with soil either contracting or expanding from its initial loose or dense state.

Investigating a different type of root system (Table 1), i.e., dense root architecture, Fraccica et al.[72,71] tested the effect of roots development on soil porosity variations, finding an overall increase in porosity and pore sizes in the vegetated specimens due to a "group effect" induced by dense and thin roots.

Also, nutrient-rich soil promotes healthier plant species, boosting root density, traits, and development.[186] This leads to an increased number of fine roots, responsible for water and nutrient uptake.[59] This point has been discussed by Ng et al.,[138] who conducted laboratory-scale experiments in a controlled environment using three replicates of columns filled with heavily compacted (relative compaction about 95 %) silty sand vegetated with S. heptaphylla (Ivy tree), compared with both vegetated columns without addition of NPK water-soluble fertiliser, and bare columns as a control. After six months, the nutrient-supplied soil exhibited a 350 % increase in leaf area index (LAI) and a 133 % increase in root area index (RAI) compared to nutrient-poor soil. The soil-roots interaction may also be affected by the soil amendments, which impact the root traits and pore spaces. To give an example, Quinteros et al.[159] conducted a study on the effects of gypsum and organic waste amendments (food waste and açai residues) on vegetation growth. They changed the soil properties of a Bauxite residue soil from a disposal area in Brazil, finding that gypsum is key for plants to thrive and develop a deeper root system.

Among the biological processes within the SVA interaction, the role played by fungi is found to be very relevant in specific conditions, as indeed, determined with reference to the effect of Mycorrhizal fungi on the plants' ability to overcome periods governed by strongly limiting factors to the vegetation growth and biological processes. In particular, Graf et al.,[81] quantified the Mycorrhizal effects on different plant and soil functions related to slope stability conditions. Results on plant growth and survival as well as on soil aggregation and slope stabilisation shown that Mycorrhizal fungi considerably and positively contribute to plant growth, survival, soil stability and corresponding slope stability functions of plants, e.g. interception and evapotranspiration.[81]

The beneficial effects of roots to ground reinforcement have been intensively investigated in the past, and they are very well acknowledged in the literature.[156,157,224] A detailed review of the proposed models to simulate this root reinforcement was given by Wu.[223] Among these models, the behaviour of the single root is assimilated to that of an elastic cylindrical fibre of high tensile strength and, in other models, to that of a flexible cable or a pile stressed by horizontal forces. As early as the 1980s, Waldron[215] and Wu et al.[224] introduced the concept of the direct effect of roots in favouring the soil shear strength, starting from the well-known simplified reinforcement model for the single root.[83] Traditionally, the mechanical effect of roots is regarded as an increase in shear strength, $\Delta\tau_r$, as a function of the root tensile strength and the soil friction angle ϕ' (Table 1). The beneficial effect of a single root is then extended to the whole root system permeating the soil,[129,172,22,32] leading to simple semi-empirical equations for evaluating the increase $\Delta\tau_r$ of the rooted soil. However, such equations do not consider a mechanical feedback loop that is the mechanical properties of the soil (i.e., its shear strength and its stress-strain behaviour) can be impacted by roots. A more advanced probabilistic approach, also validated in the laboratory and the field, was proposed by Schwarz et al.[175,173] considering the progressive failure of root bundles in different soil conditions as a function of soil deformation. Moreover, it should be noted that the shear strength increase as effect of the roots, $\Delta\tau_r$ (Table 1), is generally added as a "cohesive" term to the shear strength of the not vegetated soil, the latter being computed according to specific failure criteria, e.g., the ones for partially saturated soil condition proposed by Fredlund et al.[74] and Vanapalli et al.,[211] or Lu and Godt[119]. However, only few studies have investigated the effects of roots also under axial compression, e.g., Wu et al.,[225] Schwarz et al.[176]

At this basic level of complexity, where coupled mechanical-hydraulic processes related to the presence of roots in the soil are disregarded, recent attempts at investigating the mechanical feedback loop have been reported in the literature. As an example, the results of triaxial tests on pyroclastic soils containing varying levels of root biomass show that in drained conditions, the presence of roots led to a reduction in the volumetric strain, while in undrained triaxial tests, a general reduction of the excess pore-water pressures was observed, with a possible inhibition of the static liquefaction occurrence.[68]

As a matter of fact, the presence of roots undoubtedly implies an additional soil phase, with stress redistributions[104,105,6,63,7] and state variable modification.[220] Controlling stress and state variables, in turn, allow to properly interpret a vegetated soil's behaviour. These issues increase the complexity of examining the geotechnical behaviour of vegetated soil, particularly with traditional geotechnical testing, equipment and procedures. Therefore, studies that provide correlations between root features and mechanical soil properties may be of relevance for a more reliable use of this approach in geotechnical applications.

4. Soil-Roots-Water (*HM*) interaction: intermediate level of complexity

This section discusses some aspects of the hydro-mechanical (*HM*) coupling processes relevant for the behaviour of vegetated soil. Despite extensive recent studies, this level of analysis still requires a deeper understanding of the complex phenomena involved. Below, an attempt is made to illustrate some of these examples, aimed at identifying the most relevant hydro-mechanical processes occurring within the roots-soil mutual interaction (*HM* interaction, see Table 1). As already highlighted in the previous section, plant roots modify the soil fabric, thus progressively affecting the hydraulic and mechanical properties of the soil. Moreover, plants can extract water from soil, affecting its volume change behaviour and microstructure (i.e. shrinkage of the matrix and macro-pores volume increase, see[71]), with consequences on soil tensile and shear strength under partially saturated conditions[69,70,80] and soil collapse behaviour upon wetting.[26]

Conversely, the soil hydro-mechanical behaviour also mutually influences the features of the roots. For instance, soil wetting and drying cycles in soil and water stresses (i.e. hydraulic states above the wilting point) affect root physiology (i.e. root decay[140,141]), root volume (i.e. root shrinkage and swelling; see[29]) as well as root's Young modulus and tensile strength.[236] Also, the biomechanical properties of the roots are affected by their intrinsic hydrological state, which in turns plays a crucial role. Indeed, tensile strength tests carried out on roots of various herbaceous plants[236,61] showed that the root moisture content significantly impacts the variability of root tensile strength.

Regarding the hydraulic behaviour of the soil-root composite, the effects of the growth and volume of the roots within the soil is found to modify the saturated hydraulic conductivity, k_{sat} (Table 1) and the soil water retention curve. However, the results reported in the literature do not highlight a unidirectional effect since the root-induced modifications of the saturated permeability and the water retention curves depend on the type and state of the soil and the vegetation adopted. Ng et al.[137] and Ni et al.[142] found that the presence of one plant species generally reduces k_{sat} compared to that of bare soil, whereas mixed species and/or high plant density increase permeability. This can be explained by the competition among plant individuals that increases soil macro-porosity associated with root decay.

The soil-root-water interaction in pyroclastic soils has been extensively studied in the literature since such deposits are widespread in Mediterranean regions, where vegetation is flourishing. Furthermore, it is worth considering that these regions are widely susceptible to high hydrogeological risk due to the geo-hydro-mechanical setting within this context. Hence, the interest in deepening the knowledge about the possible favourable effects of vegetation on geotechnical systems in this context was the subject of intense scientific effort. In particular, several studies have investigated mainly the mechanical reinforcement of the vegetation in these contexts, i.e., Sarno Mountains (Campania region, southern Italy), where several debris flows under medium to high-intensity and prolonged rainfall occurred in the past.[24,30,53,55,84] In this context, given the shallowness of these landslides, the hydro-mechanical soil-vegetation coupling is a key factor in the assessment of landslide hazards.

As such, it is considered interesting to focus also on the hydraulic behaviour of such peculiar rooted soils. An example of a comprehensive investigation aimed at determining the physical and hydraulic properties of the rooted soil has been reported by Dias et al.,[56,57] within which determinations of the soil porosity, n, the saturated hydraulic conductivity, k_{sat}, saturated volumetric water content, θ_s, air entry value, *AEV*, the Van Genuchten parameter n_v, and the residual water content, θ_r, were carried out on pyroclastic undisturbed soil samples collected at a test site on Mount Faito, with and without roots. All determinations are plotted against the dry root biomass-to-soil mass ratio (%) in Fig. 3. Mature Castanea sativa, commonly known as sweet chestnut trees, is widespread on site. The understory is dominated by Pteridium aquilinum, which is cut and removed at the end of the dry season. Details of the experimentation are reported in Dias et al.[56,57] The data reported

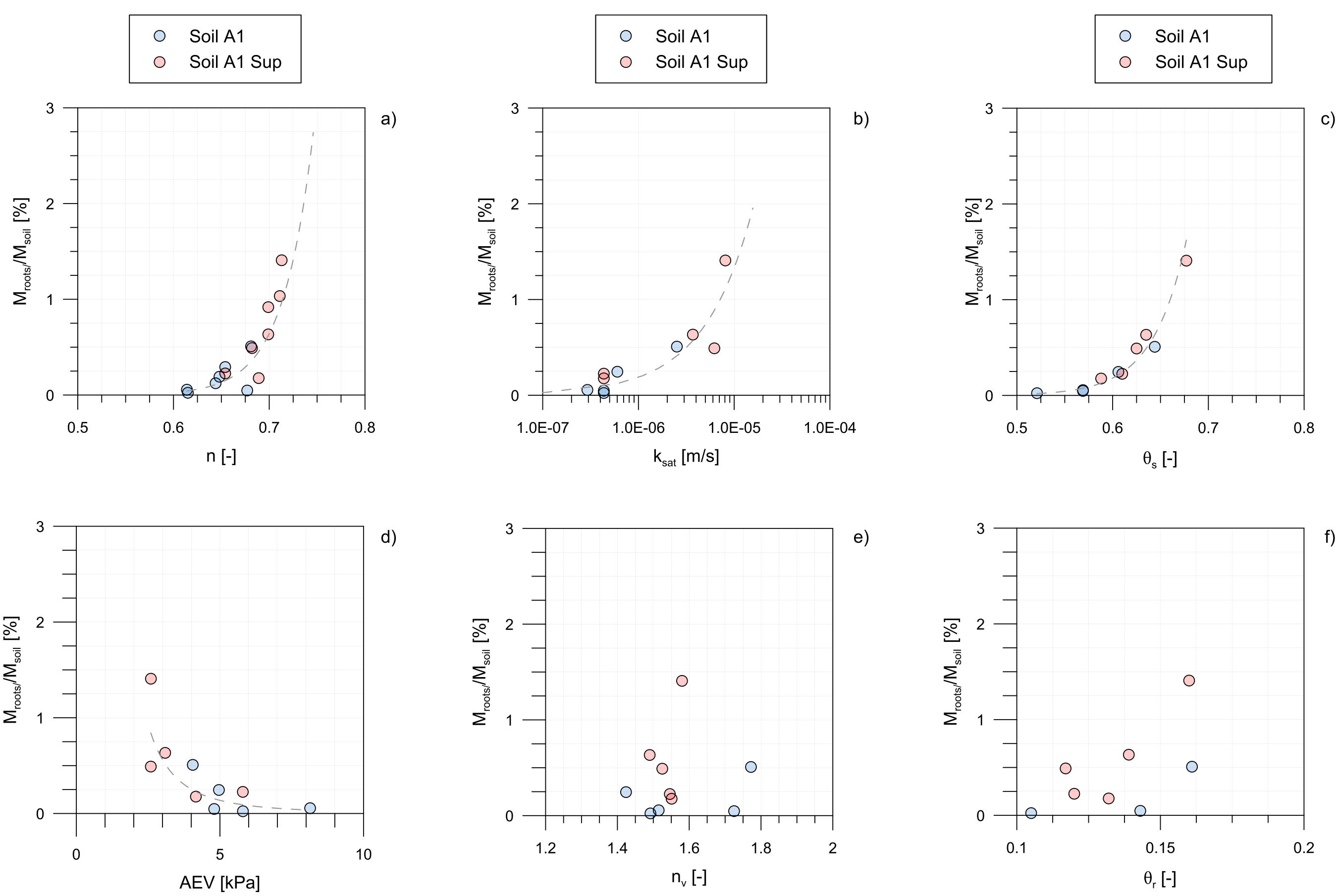

Fig. 3. Soil porosity, n, a) saturated hydraulic conductivity, k_{sat}, b), saturated volumetric water content, θ_s, c), air entry value, *AEV* d), the Van Genucthen parameter n_v e), residual water content, θ_r f) against the ratio of the dry root biomass to the soil mass. Plots modified from Dias et al.[56,57].

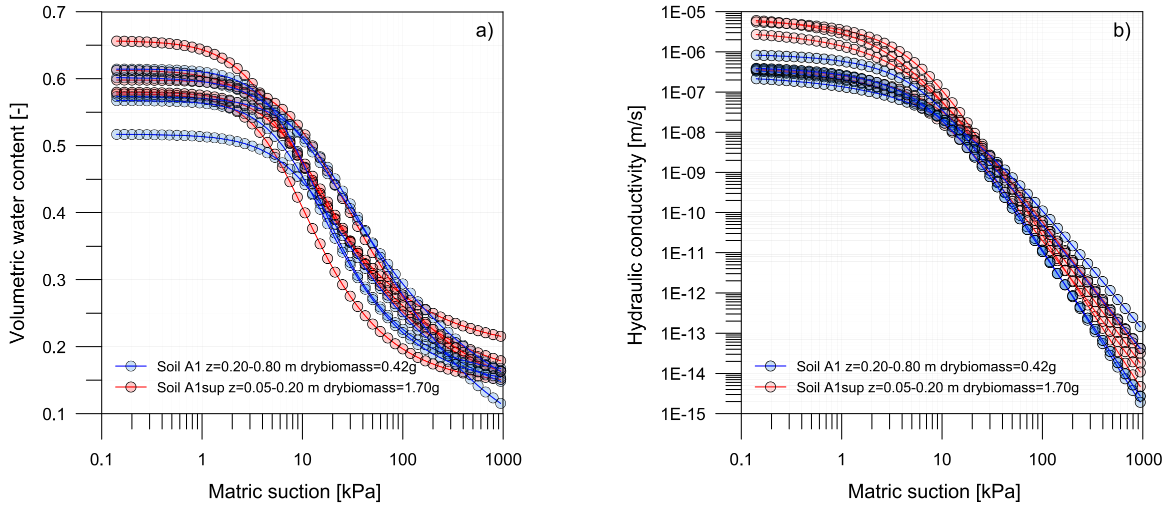

Fig. 4. Soil water retention curves a) and hydraulic conductivity functions b) determined along main drying path on specimens from layer A1 sup (continuous lines) and layer A1 (dotted lines). Plots modified from Dias et al.[56,57].

belongs to the same material but sampled at different depths; in particular, the layer A1sup (mean sampling depth: 0.05 m) and the layer A1 (mean sampling depth: 0.50 m).

A clear increase of soil porosity and saturated conductivity was found with root dry biomass, M_{roots} (Fig. 3a, b), potentially due to preferential flow induced by drying and wetting cycles as experienced during plant growth.[212]

In addition, undisturbed rooted soil samples were also subjected to drying–wetting cycles according to the experimental technique developed by Nicotera et al.[143] It allowed to determine the soil water retention curves and hydraulic conductivity functions, as reported in Fig. 4. The continuous lines refer to specimens sampled from layer A1sup, while the dotted ones refer to specimens from layer A1. The experimental data were fitted by the Mualem van-Genuchten model via inverse analysis.[143,56] By comparing the curves of these two layers, soil specimens with higher dry biomass content (layer A1sup) exhibit higher saturated water content (θ_s), a lower air entry value (*AEV*), and greater hydraulic conductivity at low matric suction levels below the air entry value. Therefore, the coarse characteristics of the soil are amplified by the presence of roots. However, vegetation seems to affect the curves in the portion of low suction, below 10 kPa, according to the findings on sandy silt reported by Jotisankasa et al.[95] It was also found that M_{roots} is well-correlated to θ_s (Fig. 3c) that tends to increase with the amount of dry biomass. This result may be attributed to the root exudation: the compound exuded around the roots tends to increase the volumetric water content near saturation. Furthermore, it was found that the M_{roots} affects the *AEV* (Fig. 3d): the *AEV* decreases (from 8 kPa to 2 kPa) when the root biomass increases. The *AEV* decrease in rooted soil can be a consequence of some changes in soil structure caused by roots and microbial activity in the rhizosphere because these are responsible for the formation of soil lumps (commonly referred to as aggregates in ecology studies) and preferential flow channels (continuous macro-pores). However, despite controlling the *AEV*, the roots seem not to impact the van Genuchten parameter n_v that defines the slope of *VWC*, and the residual water content; this proves that roots mainly affect the portion of the soil water retention curve, *SWRC*, close to saturation, at least for this type of soil.

Furthermore, Cuomo et al.[48] performed in-situ and laboratory investigations on fine long-rooted grasses artificially grown in loose pyroclastic soils of the Campania region. The Authors adopted three distinct grass species (later named VEG 1, VEG 2, VEG 3, respectively) referred as fine long-rooted perennial Gramineae grass species, belonging to C3-C4 category with a high-water consumptive demand and adaptive to xeric conditions.[60,189] More details are available in Cuomo et al.[48] Soil matric suction was measured weekly, before and after seeding, through a Quickdraw portable tensiometer, and the

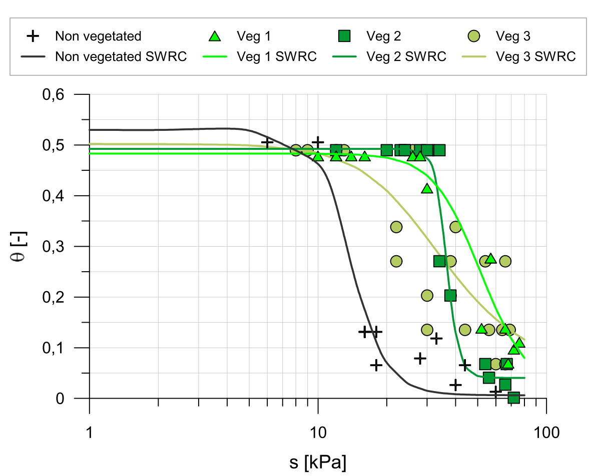

Fig. 5. Soil Water Retention Curves of non-vegetated soil (NV) and vegetated soils (VEG 1, VEG 2, VEG 3) obtained using the van Genuchten equation (modified from Cuomo et al.[48]).

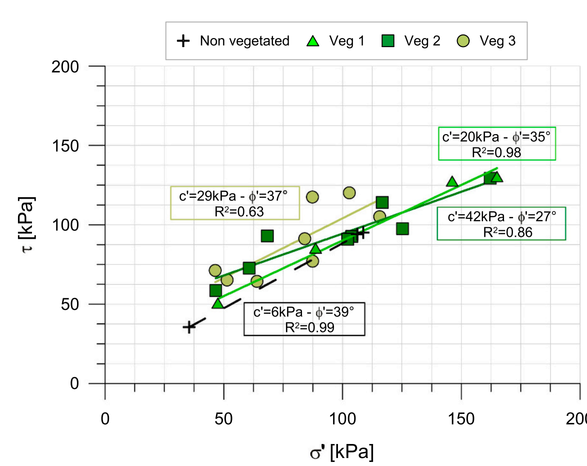

Fig. 6. Shear failure envelopes of the non-vegetated soil (NV) and the vegetated soils (VEG 1, VEG 2, VEG 3), with R^2 indicating the coefficient of determination (modified from Cuomo et al.[48]).

gravimetric water content was measured through a low-cost sensor that also allows the measurement of soil temperature, light, pH and nutrients. The field data of suction and water content were interpolated through the van Genucthen equation.[209] Furthermore, about 40 specimens of the vegetated (VEG) and non-vegetated (NV) soil were collected for laboratory testing to investigate the changes in soil shear strength induced by the long fine roots. Direct shear tests on saturated and unsaturated soils were performed at constant water content or at constant suction. The *SWRCs* (Table 1) were obtained by interpolating the field data (Fig. 5) with the van Genuchten equation, with three values of void ratio adopted in a narrow range inferred from laboratory tests. The introduction of new roots in the soil implied (*i*) a reduction of porosity and saturated water content, (*ii*) an increase in air entry value and (*iii*) a slight reduction in residual water content. These observations are consistent with Leung et al.[110] and Ng et al.[137] even if they contrast what was found by Dias et al.[56,57] and just reported above. It can be concluded that the effects of vegetation on the water retention curve of rooted soil are not unequivocal due to the interplay of multiple factors, including vegetation type, soil properties, and environmental conditions. Variability possibly arises also from differences between controlled laboratory experiments and field studies, where additional environmental variables influence outcomes. Moreover, species-specific root structures, root density, and physiological traits (Table 1) further contribute to inconsistencies across studies. In this respect, among the various possible reasons, the discrepancies just mentioned are believed to be due to the different types of vegetation studied. For instance, Dias et al.[56] investigated the interaction of the slope with natural vegetation, whereas Cuomo et al.[48] examined artificial vegetation under controlled conditions. Given this complexity, it is crucial to account for these influencing factors when analysing the impact of vegetation on soil hydrological behaviour.

The shear strength parameters were estimated based on direct shear laboratory tests, carried out on both saturated and partially saturated specimens, and adopting the effective stress framework for partially saturated soil conditions (Bishop[15]), with the χ parameter assumed as equal to the degree of saturation, S_r. For the interpretation of the experimental results, it was assumed that the roots were normal to the shear band and the assumption was supported by some former investigations.[129,232,66] Moreover, it was assumed that the effect of root configuration on the interpretation of the results of laboratory tests was negligible. Under these assumptions, the shear strength was found to increase with root-soil interaction, but each type of grass affected the failure criterion differently (Fig. 6). While the intercept cohesion of the non-vegetated soil was very low (~6kPa), the maximum cohesion was exhibited by the grass species VEG 2 (with c'~42kPa). However, also the species VEG 1 and VEG 3 exhibited a significant increase of cohesion up to reach 20 kPa and 29 kPa. Due to the intrusion of these very fine roots, the soil friction angle of vegetated soils is slightly lower than in the original non-vegetated soil.

Significant root-induced modifications of the soil water retention properties of the rooted soil were also found by Capobianco et al.[25] who reported data from vegetated (V) and not vegetated (bare) soil columns (2.0 m height, 0.2 m in diameter) to investigate the wetting-drying response of unsaturated pyroclastic soil with long-root grass. After two years of monitoring, the measured data of suction – degree of saturation (measured by mini-tensiometers and *VWC* sensors installed at four different depths) showed a tendency to flatten with time in the vegetated columns (Fig. 7), suggesting that roots were creating a soil 'virtually' denser than the bare soil.[82] This might be due to the tendency of the roots to fill the available voids and thus modify the void size distribution of the compressible soil matrix, resulting in reduced permeability and a change of structure from loose to dense soil. Also the collapse behaviour was inspected, arguing that as void ratio of rooted-soil is reduced due to root growth, the wetting-induced collapse deformation is also reduced.[26]

Fraccica et al.[71] performed soil water retention measurements on compacted bare and vegetated clayey sand samples after three months of root growth. The plant used in the study was the Cynodon dactylon, belonging to Gramineae grass species. The hydraulic path followed after static compaction (dry of optimum) to induce root growth prior to the measurements was replicated on bare samples too. Plant's growth was interrupted when roots were detected at the bottom of each sample (70 mm high), to avoid non-natural orientations and root densities within the samples. Matric/total suction measurements were performed with a ceramic tip laboratory tensiometer and a dew-point psychrometer, respectively. Suction measurements were carried out after leaving the plants in the darkness for 2 h, to stop plant's transpiration processes and, hence, to allow suction and water content equalisation and avoid potential suction-dependency on the proximity of the tensiometer to the roots of the plant individual. Measurements were complemented by X-ray and Mercury intrusion porosimetry, through which the pore size distribution (*PSD*) curves of bare and vegetated soils with different root volume ratios were reconstructed (Fig. 8a). *PSD* curves showed an increase of macro-pores (i.e. with entrance pore sizes larger than 5 μm) due to soil fissuring by the roots and a decrease of micro-pores due to mucilage production and pore's occlusion (Fig. 8a). Soil water retention

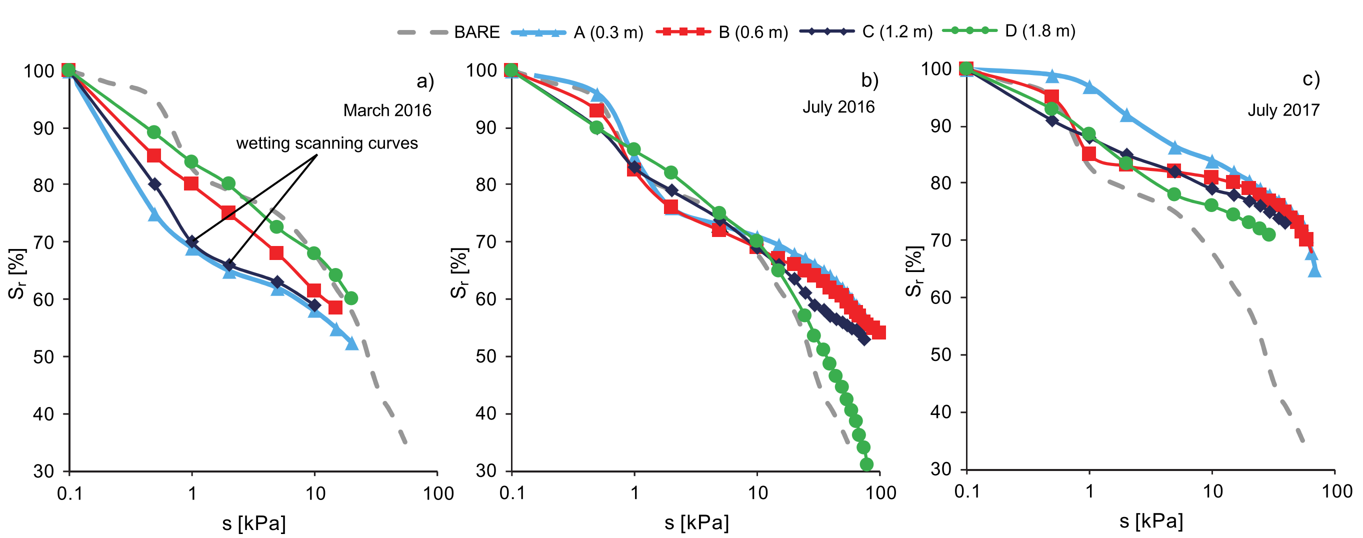

Fig. 7. Trend curves of the V column for all depths (compared with the trend curve of NV column) at three stages: (a) beginning; (b) middle vegetation growth; (c) end of the monitoring period (modified from Capobianco et al.[25]).

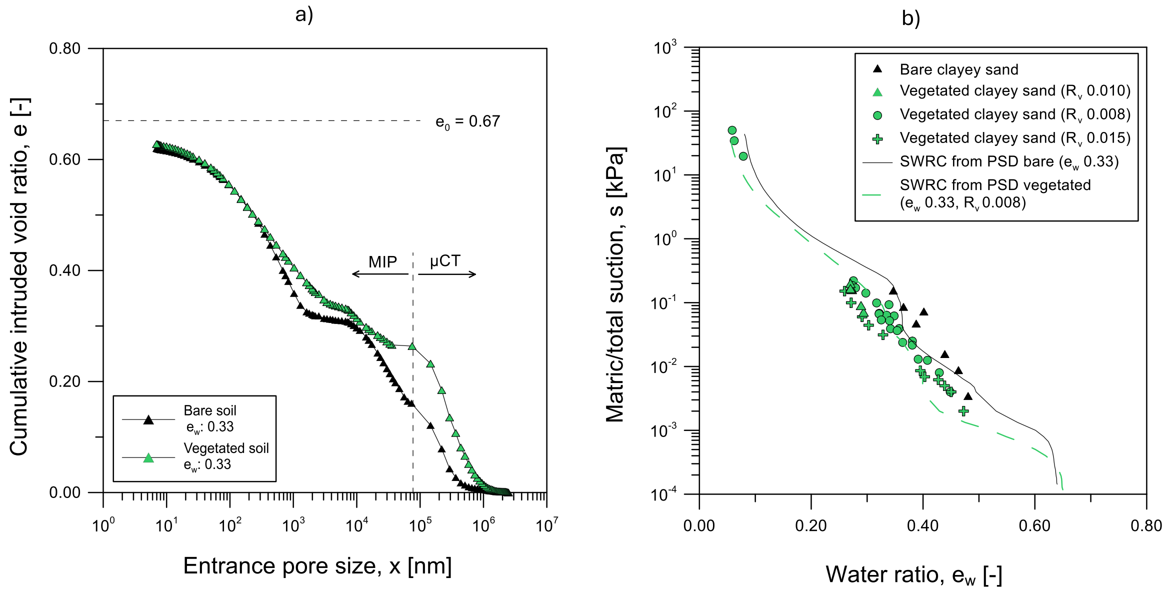

Fig. 8. (a) Cumulative pore size distribution obtained by merging MIP and X-ray micro-CT results in bare and vegetated clayey sand at water ratio = 0.33 (adapted from Fraccica et al.[71]); b) Soil water retention measurements (tensiometer + psychrometer) of bare and vegetated clayey sand and SWRC derived from pore-size distribution curves of the same soil under bare and vegetated conditions. (b) Root Volume ratios, Rv indicated in the legend (adapted from Fraccica et al.[71]).

curves were then derived from suction measurements and, indirectly, from pore size distribution curves, with good agreement between the different methods. In particular, an *AEV* and an overall retention capacity decrease were observed in vegetated samples, with particular emphasis within the samples in which the highest root volume ratios were observed (Fig. 8b). The changes in pore size distribution were used to explain the increase in saturated permeability observed in the same vegetated soil.

All the HM responses previously observed depend on the effects of plant roots on soil porosity. Considering the different root architectures and the different stresses that may develop at the soil-root interface, each plant can induce different effects on a given soil. On the other hand, different initial soil states can affect root growth and its capacity to affect porosity. Summing up, to define a framework of possible mechanisms through which plant growth affects soil porosity and soil hydraulic conductivity, Jotisankasa et al. [95] and Lu et al.[120] identified the main phenomena possibly occurring: (i) cycles of wetting and drying due to plant watering and evapotranspiration; (ii) shrinkage and decay of roots that generates preferential flow paths along the impoverished roots; (iii) obstruction of macro-pores by plant roots; and (iv) organic carbon released by plant (the so-called root exudation) and micro-pores clogging (v) re-orientation of the soil particles; (vi) soil macro-aggregate cracking; (vii) root penetration and expansion, linked to soil macro-pores development. The first two phenomena increase saturated hydraulic conductivity values (as inferred by[48,56,57,212]) while the third decreases the permeability and increases the water retention capacity (as inferred by[25]). Then, the fourth phenomenon generates a reduction of water retention capacity due to chemical effects (decrease of the water surface tension). The last three phenomena are contributing to increase the permeability as they generate an increase in macro-pores. Fraccica et al.[71] observed a combination of phenomena (ii, iv, vii) by micro-to-macro experiments, explaining the main trends obtained

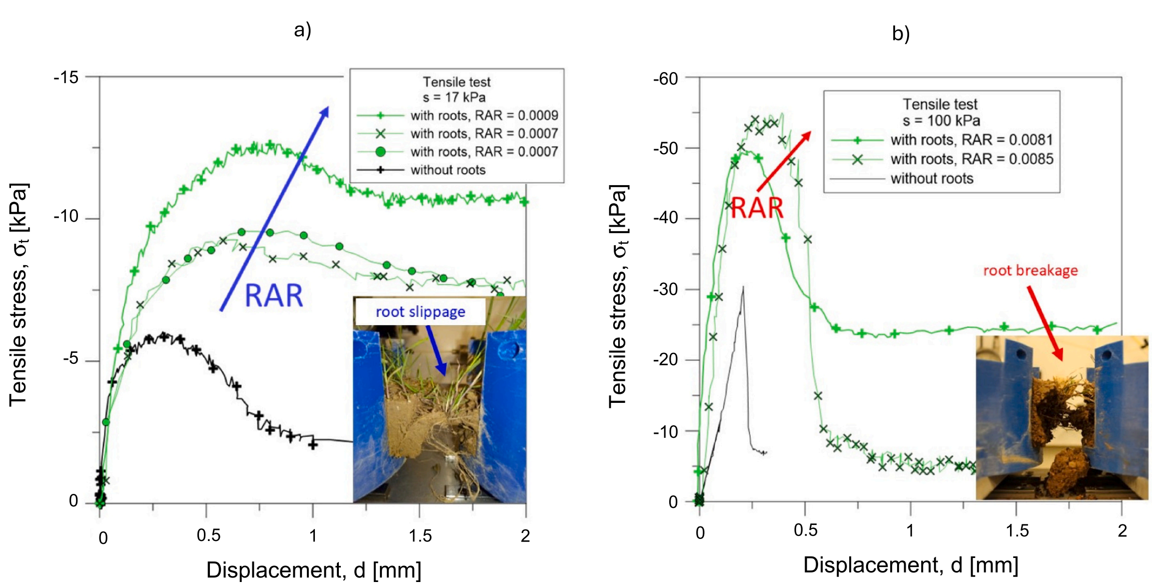

Fig. 9. Uniaxial extension tests of rooted soil with different *RAR* values and water contents, resulting in two different failure mechanisms, root slippage (a) and root breakage (b), adapted from Fraccica et al.[69] Average suction levels of the specimen tested indicated in the legend.

(permeability increase and soil water retention decrease). The combined effects of all these features concurrently are hardly quantifiable during root growth and depend on the soil type, the plant species and their interaction. Therefore, the soil-root-water interaction is expected to yield contrasting results for all these reasons.

This circumstance is also due to the chemical effects that root secretions (such as different organic matter composites and polysaccharides) and microbial communities of the rhizosphere may have on the whole root-soil composite. Indeed, the scientific literature dealing with this issue have clearly shown that the biological and chemical processes due to the vegetation growth and root penetration are associated with considerable effects on the chemo-hydro-mechanical properties of whole rooted soil, leading then to indirect modifications of the mechanical and hydraulic behaviour of the root-soil composite as well as the growth of the root itself, e.g.[5,33]

The effects of roots on soil water retention are, in turn, indirectly affecting soil shear strength in partially saturated conditions. As observed[73,211] soil shear strength depends on both suction and degree of saturation. In these regards, earlier works in literature devised empirical relationships of the shear strength of the rooted soil (or the contribution of vegetation to the shear strength) as a function of water content,[66] even if not investigating the underlying mechanism of stress increase at partial saturation.

Recent research on the hydrological and hydro-mechanical behaviour of rooted soils investigated the effects of vegetation-induced suction resulting from evapotranspiration and rainfall interception on the shear strength using large-scale direct shear testing under laboratory conditions[233] and vane shear testing at field.[21] Furthermore, the volume change behaviour of partially saturated rooted soils has only been of interest in recent years.[123,231] Both works yielded the applicability of well-established stress−dilatancy relationships to rooted soils, validated for unsaturated soils, while underlining the strong need for further research to differentiate the contributions of roots to dilatancy.

The root pull-out, crucial for the mechanical reinforcement of vegetated soils provided by roots, is usually believed to be only a mechanical process, but it is worth mentioning that it is strongly influenced also by the hydrological regime of the root-permeated soils. Indeed, experimental studies have shown a decrease in root pull-out resistance with increasing water content,[65,173] which can be attributed to the changes in bonding between root and soil particles due to higher amounts of water in the pores. Increased water content can also affect failure during pullout with roots tending to break in drier soils, while slippage becomes the dominant failure mechanism for small roots in soils with high water content,[237] whereas larger roots (> 3–4 mm in diameter breaks[156,172]).

Similar tendencies were observed by Fraccica et al.[69] through direct

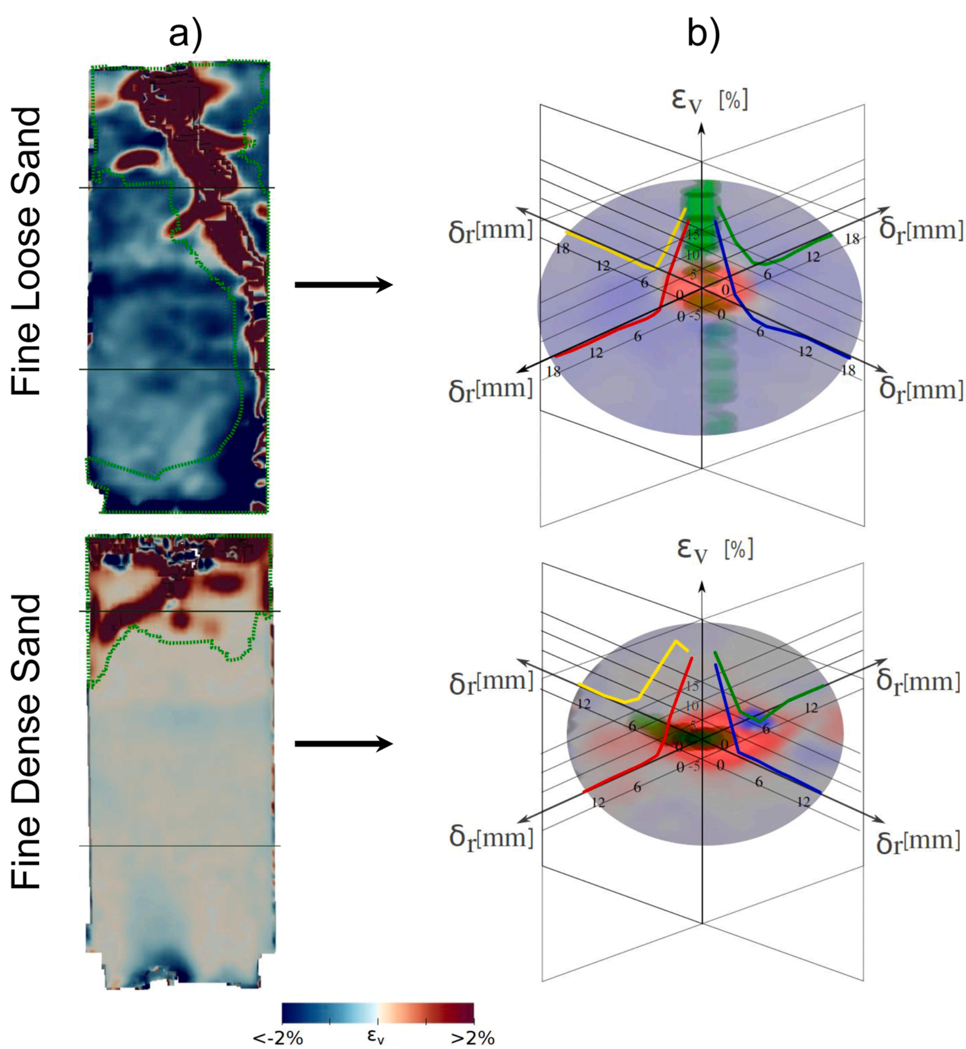

Fig. 10. Volumetric strain profile of the sheared soil, comparison between vegetated loose sand and vegetated dense sand; a) shows 2 vertical 2D slices of the volumetric strain field obtained from DIC. The dotted green line represents the contour of the sheared zone (ε_q>1 %); b) change of volumetric strain on Day 02, with respect to the distance to the roots. For each of the two samples with maize in fine sand, four profiles are displayed above the horizontal section showing roots (in green). Modified from Anselmucci et al.[6,7]

uniaxial tensile tests on vegetated clayey sand carried out at constant water content: while root slippage and ductile stress-strain curves were observed in soil at low average suction level, root breakage and a marked fragile response were observed on vegetated soil at high average suction level. Indeed, soil shrinkage around root tips and root mucilage production upon soil drying increased the points and interlocking forces between roots and soil (Fig. 9). Statistical analyses were produced, within this study, finding good correlations between soil tensile strength, hydraulic state (effective degree of saturation and suction), area, length, and tensile strength of roots. All the hydro-mechanical processes mentioned above are characterised by a progressive evolution, primarily driven by the root system growth, which is a complex and time-dependent phenomenon. As such, innovative and advanced laboratory techniques have recently been adopted to better understand the time-dependent interplay between roots, soil, and water and quantify the effects of root growth on soil properties, such as porosity and density. In conjunction with X-ray tomography, Digital Image Correlation (*DIC*) has been employed to investigate the spatial transformation of images, including translation and distortion, between the reference and deformed states. *DIC* provides insight into the evolving interaction induced by roots, revealing information on soil responses to root growth and water uptake. It was found that as plant roots grow,[6,7] they induce shearing stress in the surrounding soil, resulting in volumetric deformation characterised by dilation. Using 4D investigation combining X-ray and DIC, Anselmucci et al.[6,7] demonstrated how the soil portion encircling the root experiences significant shearing strain, as illustrated in Fig. 10. Quantifying the volumetric strain in the shearing zone reveals that this soil undergoes dilation, irrespective of initial relative density, particle size, or root diameter. The soil's initial looseness causes compaction to occur at a distance approximately 15 times the D50 particle size (Fig. 10b). In denser soils, the dilatant behaviour dissipates more rapidly with distance from the shearing root. This pronounced change in soil microstructure leads to an increase in bulk porosity throughout the system, consequently affecting the hydro-mechanical response of vegetated soil to external loads.

As a further example of a novel investigation technique, recently adopted to investigate the interactions between soil and roots, the Particle Image Velocimetry (*PIV*) allowed to evaluate the strain fields on the soil surface generated upon uniaxial extension by the presence or absence of roots and the different soil hydraulic states.[69] Using PIV analyses, while localised strain was always observed in bare soil, multiple cracks and a larger strain field were observed in vegetated soil at low suction values, suggesting a strain (stress) redistribution exerted by the roots in extension and slippage. Dryer vegetated soil exhibited a response between the previous two, with a less evident strain redistribution, a more localised crack and a more fragile response both in roots (breakage) and soil.

As such, it can be concluded that despite many studies have assessed the effect of plants on soil hydraulic behaviour recently reviewed by lu et al.,[120] counterposed responses have been recorded depending on the soil type, initial hydro-mechanical state, and plant species.

5. Soil-Vegetation-Atmosphere (*THM*) interaction: third level complexity

At this third level (see Table 1), the complexity of variables and processes that control the SVA interaction becomes noticeable. In this scenario, the soil and vegetation interact not only with each other, modifying the hydro-mechanical behaviour of the soil-root composite (first and second-level complexity) but also with the atmospheric variables. Specifically, the vegetation plays a crucial role in rain interception, rainfall infiltration, and transpiration flux. Therefore, a comprehensive study of the Soil-Vegetation-Atmosphere (*SVA*) interaction necessitates a thermo-hydro-mechanical approach.

When dealing with natural slopes, the main variables defining the thermo-hydro-mechanical state of the slope soils have been identified by

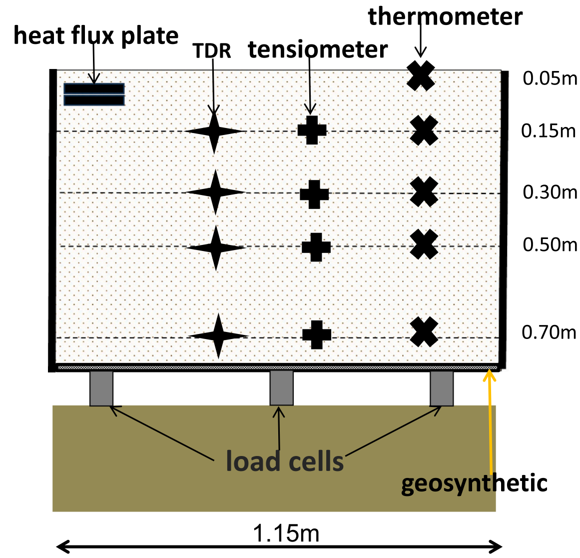

Fig. 11. Scheme of the physical model (modified from Rianna et al.[162]).

Elia et al.[62] as follows: (*i*) the pore liquid pressure (scalar P_l); (*ii*) the pore gas pressure (scalar P_g); (*iii*) the temperature (scalar T); (*iv*) the solid phase displacement (vector u). The balance equations essentially control the values of these variables: (*i*) mass balance of liquid, variable P_l (kPa); (*ii*) mass balance of gas, variable P_g (kPa); (*iii*) internal energy balance for the medium, variable T (degrees); (*iv*) momentum balance for the medium, variable u (m). Since all the processes determining the variables are coupled in the soil, to guarantee that specific aspects are not ignored, potentially leading to misevaluation, all the four balance equations reported above should be solved numerically within a mutual coupling numerical iteration scheme.

The physical variables involved in the processes are controlled by physical laws (Table 1), such as the law expressing liquid and gas flow, the diffusion law, the change of phase law and the constitutive law of the soil skeleton. In the framework of hydraulics of porous media, the laws used to simulate some of the basic processes involving the pore fluids are Darcy's law to describe either the liquid or the gas advective flux and Fick's law for the vapour and the air non-advective fluxes. Furthermore, Henry's law may be used to predict air dissolution in the liquid phase, the psychrometric law to correlate suctions and relative humidity values at a given temperature, and to predict the transition of water from the liquid to the gas phase. Fourier's law describes conductive heat fluxes through the fluid or the solid skeleton.[62] Moreover, soil constitutive laws are required in the integration, which are typically the *SWRC* (Table 1)

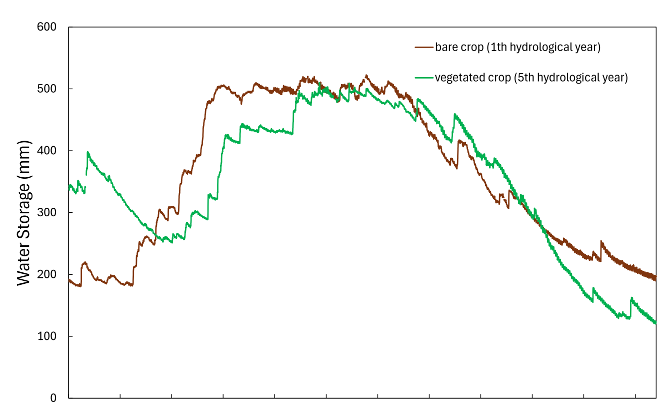

Fig. 12. Evolution of water storage and potential evaporation under two hydrological years under bare and vegetated conditions (modified from Pagano et al.[147]).

expressed as the variation of the volumetric water content, θ, or the degree of saturation, S, with the soil porosity, n, and the soil suction, s; the hydraulic conductivity function, k (s, n, T); the mechanical constitutive law; the thermal conductivity law (Table 1), which depends on T, S and n; the air conductivity law; and the diffusion and the dispersion coefficients, both dependent on T, S, n and P_g.

When the level of accuracy of the analysis or predictions of the SVA interaction on purpose is high, the whole THM set of processes has to be accounted for. As such, specific monitoring activities need to be carried out to investigate the SVA interaction from a phenomenological point of view concerning specific case studies. To this extent, it is usually more convenient to adopt physical modelling or full-scale tests rather than laboratory-controlled tests. Indeed, the energetic, hydraulic and mechanical response of the soil can be better and more realistically observed when the atmospheric forcing action corresponds to the natural transient conditions occurring throughout a whole hydrological year and/or a whole vegetation cycle, i.e., from September to August.

When adopting physical modelling, a lysimeter is often used since this is a large apparatus adapted to measure water mass and energy fluxes in a soil domain. An example of using a lysimeter to assess the interaction between the soil, the vegetation and the atmosphere has been conducted by Rianna et al.[162] concerning silty volcanic soils, largely outcropping in the Campania region. The lysimeter was adopted to quantify rainfall infiltration, actual evaporation and hydrological effects on volcanic sloping covers susceptible to rainfall-induced (Fig. 11). The physical model was exposed to weather conditions recorded by a meteorological station under bare conditions over the first three years and vegetated conditions (sowing gramineous plants) over the following five years.

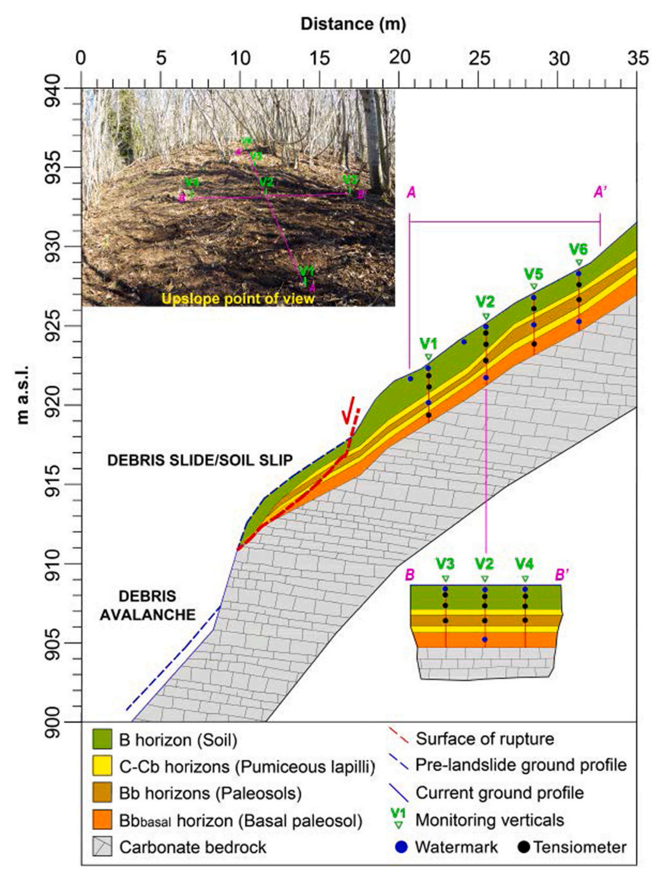

Fig. 13. Geological model of the monitoring station site reconstructed by field investigations, location of the monitoring verticals (V1-V6) and approximate position of tensiometers and Watermark sensors. In the upper-left box an upslope-oriented photo of the monitored plot is also shown (modified from Fusco et al.[77]).

Three load cells were also placed below the tank to monitor the weight of the whole structure and, correspondingly, the evolution of water storage, along with the linked amounts of infiltrating rainfalls and actual evaporation. The monitoring system was conceived to measure all the different fluxes involved in the energy balance at the soil atmosphere interface (i.e., net radiation, sensible heat, downward heat flux) and also the TH soil state variables within the layer at different depths, i.e., soil matric suction, volumetric water content and soil temperature. The authors determined that in both cases, i.e., vegetated and bare conditions, potential infiltration decreases with increasing the soil wetting state. This implies that the progressive lowering of entering gradients due to suction drops affects potential infiltration more than the progressive increase in soil hydraulic conductivity.

Fig. 12 plots typical monitoring data of the water storage evolution observed over two hydrological years with the layer tested under bare and vegetated conditions.[147] Over the wet periods, the water storage initially increases due to infiltrating rainfall that prevails on evaporation. It then stabilises at a wet threshold when the layer starts to experience drainage from the bottom (breakage of the capillary barrier) and low levels of potential infiltration. At this wet threshold, only very persistent events are suitable to induce further increases in water storage,[162] as verified by a prolonged wetting test.

Over dry periods, water storage decreases, brought low by evaporation (bare conditions) or evapotranspiration (vegetated conditions) prevailing on rainfall infiltration, and finally attains a dry threshold. This last significantly differs between bare and vegetated conditions. Under vegetated conditions, the sharper decreasing trend leads to a final dryer state with a lower dry threshold. The enhanced desaturation processes take place thanks to the water uptake mechanisms activated by roots, which are suitable for extracting water everywhere in the layer for the state change. The entire layer is thus involved in the desaturation process, as opposed to the layer's shallow zones, which are only concerned with bare conditions.

In field conditions, the difference between the wet and dry thresholds represents a storing potential of rainfall water that forms during dry periods and is exploited during the subsequent wet periods for adsorbing water under stable conditions for the layer. Instability relates to a wetting state of almost full saturation at any depth, corresponding to a water storage that exceeds the wet threshold.[162] The enhanced spread between wet and dry thresholds induced by vegetation increases the layer's ability to safely store more significant amounts of rainfall water without crossing the wet threshold towards unstable conditions.[147]

A field monitoring of the soil-vegetation-atmosphere interaction was experimented close above a source area of a landslide involving ash-fall pyroclastic soils in the Sarno Mountains (Campania region, southern Italy), covered, as typical, by a deciduous forest of chestnut (Castanea sativa) and subordinately hornbeams (Carpinus betulus) and maples (Acer campestre).[77] To such a scope, tensiometers, Watermark (Irrometer Inc.) and MPS-2 dielectric sensors (Decagon Inc.) were deployed along 6 measuring verticals drilled across the whole thickness of the soil mantle (locally about 4 m) and according to different soil horizons (Fig. 13). Roots apparatuses were recognized as characterized by a decreasing Root Area Ratio (*RAR)* with the depth, ranging from about 0.20–0.08 %, respectively for the shallower B soil horizon and the deepest Bb one. The results revealed a composite temporal variability of suction, from the daily to the seasonal time scales, related to rainfall patterns and evapotranspiration regime. Unsaturated conditions were always observed with values of suction ranging at the annual scale from about 3kPa to, and beyond, 200kPa. Frequency analyses of suction for each soil horizon showed: a) a strongly delayed timing, determining (in winter and summer) an opposite behaviour between the shallowest and deepest soil horizons; b) the involvement of the whole ash-fall pyroclastic soil cover in the seasonal hydrological dynamics. Therefore, the hydrological regime of the soil mantle was recognized as characterized by a strong seasonal variability, depending on the precipitation and evapotranspiration patterns induced by the vegetation cycle of the local deciduous forest, thus controlling the slope stability.

Another field investigation of the effect of vegetation on the thermal behaviour of soils was reported by Oorthuis et al.[146] In this study, an embankment with a southern and northern exposure was parcelled out to have vegetated and non-vegetated portions. Each portion was monitored with heat flow sensors and thermometers at different depths in the soil. Concerning thermal aspects, vegetation was found to reduce the incidence of net solar radiation and, thus, the heat flow within the soil. On both exposures, the presence of vegetation resulted in lower maximum temperatures and higher minimum temperatures in the soil compared to the respective non-vegetated portions.

A full-scale vegetated test site has recently been reported by Tagarelli & Cotecchia.[193] In particular, an area of about 2000 m^2 was seeded with selected Gramineae crops within the toe area of an active deep landslide in a clayey slope.[44,190,191] The test site was equipped with sensors to monitor the SVA interaction over time, i.e., the soil and vegetation states, and the forcing atmospheric action. The impact of the weather action on the soil state was monitored, both within the vegetated area (i. e., selected gramineae crops) and outside it, where only spare and spontaneous wild plants occur. The properties of the rooted clayey soil cover were investigated in the laboratory and in-situ in terms of both saturated permeability and retention properties.[195,196] All the measurements were consistent in showing that roots impact the hydro-mechanical properties of the rooted soil by increasing the permeability and reducing the retention properties of the soil-root composite material. The selected gramineous plants vegetation was found to impact the thermo-hydro-mechanical soil state at depth compared to the soil state in the area where only sparse and spontaneous vegetation is present. It was found that, despite the selected vegetation causing an increase in the saturated permeability, the soil state at depth in the vegetated area was characterised by lower water content throughout the whole hydrological year than the soil at the same depth but outside the vegetated area. This circumstance, also corroborated by the recorded suction levels in the soil, testifies that the water flux infiltrating through the ground surface was decreased due to the combined effect of the aerial portion and root system of the selected vegetation compared to what was occurring in the area of the spontaneous and sparse vegetation.[193]

In parallel with experimental studies exploring the complexity underlying the coupling of all THM processes within SVA interaction, significant advancements have also been achieved in numerical simulation capabilities. These advancements are crucial in the context of SVA interaction, as among the final purposes of this research activity is to predict the THM processes and design sustainable and effective interventions. Accordingly, the following section summarises recent developments in numerical modelling methods aimed at addressing SVA interaction, drawing inspiration from the increasing complexity of analysis levels, from mechanical (M) and hydraulic-mechanical (HM) to thermo-hydro-mechanical (THM) coupling.

6. Recent insights on the numerical modelling of the SVA interaction

The numerical prediction of the soil state in interaction with the vegetation and the atmosphere within a boundary value problem has been a topic of scientific research in the recent past, aiming to provide methodologies to depict a framework for practical applications.[62] Indeed, different levels of numerical modelling complexity of the SVA interaction have been presented by Elia et al.[62] highlighting the strengths and limitations of each level of numerical prediction.

In early developments, only simplified strategies to predict the SVA interaction have been adopted and reported in the literature, e.g., *H* uncoupled (e.g.,[201,152,190,194]), *TH* coupled (e.g.,[147,85]) and coupled *HM* (e.g.,[150,191,192,204,203]), since fully coupled THM modelling was still too complex to carry out.

However, despite the experience gained when adopting simplified approaches, i.e., H and HM, determining water fluxes associated with the energy balance, which is neglected and not solved, remains an ongoing research challenge. Indeed, the evaporation and transpiration fluxes must be an input boundary outflow at the ground surface, meaning that those fluxes have to be estimated using phenomenological interpretations and semi-empirical laws, e.g., Penman[151]; Monteith,[132] Allen et al.[3] However, in this case, a root water uptake (*RWU*) model must be employed to define the intensity and distribution of the transpiration flux over the root depth.

RWU distribution is often treated as a function only of the vertical dimension. However, the use of 1D *RWU* models may be suitable for crops with uniform RWU patterns; nevertheless, for row crops, high-stem plants in rows, or single-stand high-stem plants, the adoption of multidimensional *RWU* models (e.g.,[36,217]) is necessary due to the increased complexity of water uptake patterns to describe.

It is worth noting that the knowledge of the geometrical distribution of roots in the soil is one of the major sources of uncertainties encountered in SVA modelling, and this may represent an issue when adopting and calibrating a *RWU* model, since the spatial distribution of the transpiration flux with depth is closely linked to the architectural features (i.e., spread, depth) and the root density distribution of a specific root system. The parameters of the *RWU* models, describing the spatial variability of *RWU*,[153] can be measured directly by applying destructive methods (root coring), non-destructive but disturbing methods (use of rhizotubes and mini-rhizotubes) or by employing punctual monitoring on the plat xylem as recently carried out by Dainese & Tarantino.[50] Traditionally rooting patterns are directly investigated by root coring. It allows the definition of root geometrical attributes such as the Root Length Density (*RLD*), which is an important indicator of the potential *RWU* and the most used to characterise root system[177] because the finer roots (the most active in terms of water uptake) receive higher weighting compared to large inactive roots.[36] The hypothesis is that the obtained *RLD* spatial distribution with depth is coincident with the *RWU* pattern, and the parametric function expressing the distribution of *RLD* can be used to describe the fraction of total uptake intensity occurring at each point of the rooted soil volume.[36] Destructive methods are cheap and fast not only for their sampling procedures but also for the elaboration of the data thanks to new Image Analyses Techniques (*IAT*) (among others,[36]) and to X-Ray Computer Tomography (among others,[51]). However, destructive methods may have a relevant incidence on the future growth of the plant by altering root bulb natural development, especially if sample extractions are performed multiple times over a long investigation period.

Many studies have indicated that the actual patterns of *RWU* are the result of a complex interplay between *RLD* and various soil factors (such as water content, nutrient levels, and aeration status) (among others,[144]). The flexibility and adaptability to these factors of a root system can lead to discrepancies between the *RLD* pattern and the actual RWU distribution, constituting a particular challenge for models that rely solely on *RLD*.[35]

From this comes that realistic modelling and predictions of *RWU* patterns must rely on both *RLD* patterns and in situ measurements of pore water state (water content and potential) and fluxes with time.[180] Observational data are used to calibrate the parameters of the *RWU* spatial distribution function to ensure that the model accurately simulates the water dynamics of the rooted soil. Inverse modelling is a suitable method for deducing soil and root properties from observational data in this context. Through optimisation algorithms, inverse modelling approaches systematically search for parameter values that yield the best possible match with field observations.[90] In scientific literature, measurements of moisture distribution using soil water content *TDR* sensors and heat pulse sensors (e.g.,[36]) and of water potential data, even if fewer in number, employing tensiometer and/or water potential sensors (e.g.,[23,14]) have been documented in rooted soils. These measurements are being used successfully to calibrate *RWU* spatial distributions, and they are showing promising results.

Only recently, within the literature even more sophisticated modelling schemes for the prediction of processes with the *SVA* interaction have been introduced. These models aim to address boundary value problems on a field scale, incorporating flexible geometries and advanced features. For example, Badakhshan et al.[11] describe thermo-hydro-mechanical simulations using a 3D Finite Element program that includes boundary conditions representing the *SVA* interaction and non-linear *RWU* source-sink terms. The approach ranges from simple to complex empirical constraints combined with the Richards' equation[164] to account for the effects of air and soil temperature on plant transpiration.[139] In more recent models,[11,122,139,200] the relationship between *RWU* and temperature is based on the weighted stress index and adjustments to canopy resistances, which depend on the potential transpiration rate influenced by temperature, since the latter impacts the opening and closing of stomata.

The numerical models are able to predict soil temperature fluctuations smaller in vegetated areas than in bare soils because of solar radiation interception, coherently with field and laboratory data.[145,146] By accounting for the thermal equilibrium between soil and vegetation cover, in the numerical model the evaporation flux is calculated based on the vapour concentration difference between the atmosphere and the soil surface. Within the numerical modelling scheme proposed by Badakhshan et al.,[11] the vegetation is modelled through three resistances located at the soil/canopy, within the canopy, and at the canopy/atmosphere interfaces. These resistances are dependent of factors such as solar radiation, vapour pressure deficit, and soil water content.[113,221] Also the relationship between canopy resistances and environmental conditions varies among plant species and are influenced by soil type. This latter numerical scheme is in contrast with more traditional approaches, where *RWU* and canopy resistances are expressed using an empirical function that ranges from zero to one.[229] These empirical approaches often consider interconnected rhizosphere layers, allowing soil water to flow between layers based on average root hydraulic conductivity and water potential gradients.[167,100] Recent models represent canopy resistance by linking it to solar radiation, vapour pressure deficit, and soil moisture content.[107]

7. How much can we rely on roots' effects in geotechnical engineering practice?

The approach for interpreting and modelling *SVA* interactions, as outlined in the previous sections, provides a possible reference framework. However, it still requires a methodological procedure to determine the most appropriate level of complexity (e.g., *M*, *HM*, *THM*) to be applied to the specific problem at hand. To this end, the already cited Table 1 (see Section 2.2) summarizes the key quantities and parameters that need to be measured or derived for each level of complexity, based on specific methods, procedures, laboratory tests, and in situ testing. In particular, Table 1 serves as a guide for identifying the most relevant properties and features of the soil-root composite for each coupled mechanism at the respective level of complexity. The table also details the input required for analysis and numerical modelling (e.g., root geometry, tensile root strength, and soil-water retention properties) and outlines the common measurement techniques, such as field surveys, laboratory testing, in situ testing, and numerical back-analysis, used to obtain these inputs. Additionally, relevant studies that have advanced the understanding and modelling of the involved properties are cited, offering a valuable resource for researchers working on SVA interaction.

Overall, the case study examples presented in Table 1 (see Refs. in the last column of the table), combined with advancements in the numerical modelling of *SVA* interactions just reported, demonstrate that the implementation of the complex coupled *THM* processes outlined in this contribution is now feasible. In particular, these examples highlight both the capabilities and limitations of existing experimental procedures and numerical methods, but also pose new unexplored challenges. In fact, several issues within the *SVA* interaction still remain to be addressed by scientific researchers, since those have not been fully clarified yet. Some of them can be summarised as follows:

a) The representativeness and reliability of rooted-soil shear strength measurements: usually, in situ tests are preferred to laboratory testing; however, no standards or protocols to carry out field testing are available, despite recently adaptations of the vane test or corkscrew extraction[128] have been tested as a reasonable alternative to more common direct shear tests (e.g.[127]); in particular, recent field tests have been developed to measure root reinforcement upon tensile[173] and compressive stress,[34] showing the need of further advancements specifically when dealing with large root diameters (> 10 mm).
b) Quality of the predictions obtained from the adopted models: the mechanical reinforcement can be estimated based on root properties alone (e.g. quantity, diameter, tensile strength, in-depth distribution) using the analytical models proposed in the literature, but different models may result in a broad range of reinforcement predictions,[32,127,175] so that accuracy of the reinforcement predictions is highly dependent on the accuracy of the adopted model.
c) The spatial and temporal variability of the properties of vegetated soils: the geometry of the root system is generally far from being regular and easily predictable within the vegetated soil, especially when different plant types are coexisting together; furthermore, as consequence the soil water content and soil suction not only can differ in the space but can also vary over relatively short time windows, thus affecting the soil shear strength. The plant transpiration also depends on the weather conditions, causing a further source of suction and soil stress state variability over time; finally, spatial and temporal variation in the properties of vegetated soils could be also associated with the vegetation damage induced by earthquakes-induced shallow slips and the following natural vegetation recovery.
d) The impact of biological plant drivers on the rooted soil mechanical reinforcement: indeed, factors such as root age and anatomical development, vegetative cycle of the root system add even more complexities to the overall framework; these aspects have only been explored in a limited number of pioneering studies.[116,126,17,67]
e) The effects of plant traits, species and functional groups on the vegetation-induced soil suction: while the mechanical reinforcement is controlled by morphological and mechanical traits, the soil suction is also the result of the eco-physiological responses and adaptations mediated by morphological traits; however, the latter is still the subject of an open debate in the research community.[18,80,136]

Tackling these open challenges requires a comprehensive effort that integrates experimental advancements, refined modelling approaches, and interdisciplinary collaboration. By further exploring these aspects, future research can enhance the predictive capabilities of *SVA* interaction models, ultimately leading to more effective strategies for assessing and improving the stability of vegetated slopes.

7.1. A showcase of a multi-scale research activity providing practical insights

As an example of a first attempt to fill some of these research gaps, Boldrin et al.[18,20] carried out a series of experiments to identify the relation between plant species with different traits and vegetation-induced hydrological soil reinforcement, (research gap *e)*). This research activity is noteworthy since it progressively moved from a controlled environment[18] to a full-scale field trial on an embankment prone to failure due to uncontrolled soil and climate variability.[21] The initial study[18] investigated the impact of the gained soil strength with reference to ten woody species characterised by different transpiration rates (Fig. 14a). A linear correlation between transpiration-induced suction and the increase of shear strength was found. In this respect,

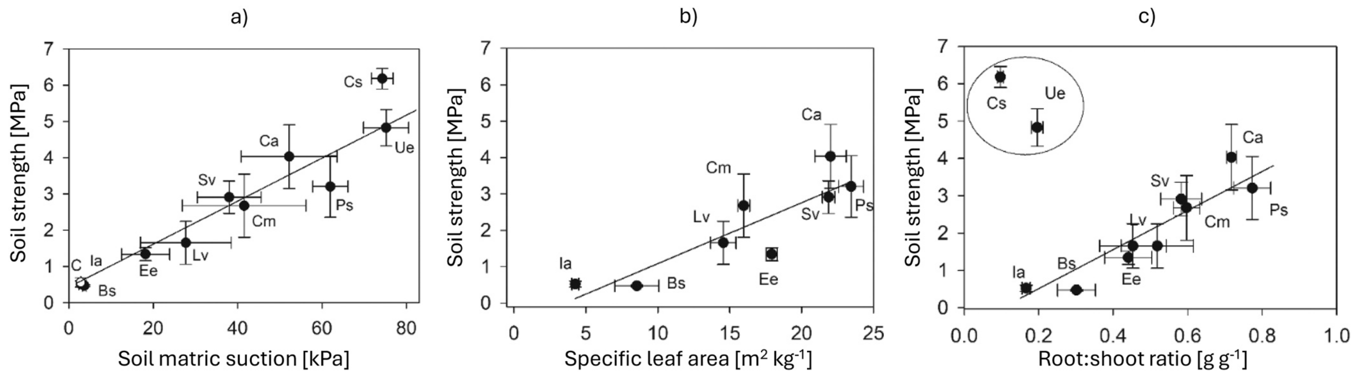

Fig. 14. (a) Relationship between matric suction and soil strength (penetration resistance) in fallow pots (C; open symbol) and planted pots vegetated with ten contrasting woody-species. Values were recorded after seven-days evapotranspiration period since soil saturation. Linear regression [f= 0.43 + 0.0593*x; P-value< 0.0001; R^2= 0.73]. Mean values are reported ± standard error of mean. Species acronyms: Bs (*Buxus sempervirens*); Ca (*Corylus avellana*); Cm (*Crataegus monogyna*); Cs (*Cytisus scoparius*); Ee (*Euonymus europaeus*); Ia (*Ilex aquifolium*); Lv (*Ligustrum vulgare*); Ps (*Prunus spinosa*); Sv (*Salix viminalis*) and Ue (*Ulex europaeus*). (b) Relationship between specific leaf area and soil strength gain induced by the contrasting species (Cs and Ue not included). Linear regressions [f= -0.59 + 0.1676*x; P-value< 0.0001; R^2= 0.50]. (c) Relationship between root:shoot ratio and soil strength gain induced by the contrasting species. Linear regressions [f= -0.65 + 5.3716*x; P-value< 0.0001; R^2= 0.54]. Cs and Ue (woody legumes) showed distinct results. Figure remade from Boldrin et al.[18].

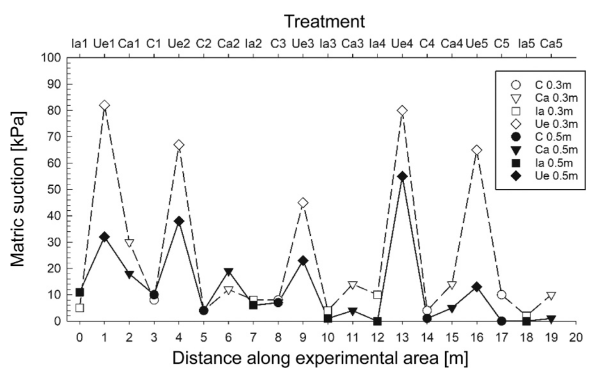

Fig. 15. Matric suction recorded at 0.3 and 0.5 m depth along a 20 m-long embankment vegetated with contrasting species during a representative day. Note matric suction peaks in *U. europaeus* plots. Acronyms: C: control plot (fallow soil); Ca: *Corylus avellana* plot; Ia: *Ilex aquifolium* plot; Ue: *Ulex europaeus* plot. Five replicates per each treatment. Figure remade from Boldrin et al.[21]

when plant traits for each species were quantified, clear relationships between hydrological soil reinforcement and both specific leaf area and root and shoot ratio were found (Fig. 14b, c). These relationships highlighted the importance of accounting for plant economic strategies (i.e., resource allocation, see[222]) when screening species for hydrological reinforcement.

Building on these results, Boldrin et al.[20] introduced soil depth (1 m) and season (summer vs. winter) as additional variables, trying to investigate the seasonal variability in temperate climate and minimum soil suction during wet periods. In this specific study, contrasting species showed differing abilities to induce suction and hence influence soil strength with depth during summer and winter. During summer, *Ulex europaeus* (legume evergreen) was able to generate a soil strength gain along the entire depth-profile inducing high suction values (e.g., 70 kPa), which were largely maintained in deeper soil (0.7 m) after wetting events. The evergreen species could uptake water during winter building up soil suction. However, it should be noted that the tested evergreens largely differed in their ability to induce soil suction because of different growth rates and resource use between legume (nitrogen-fixation) and non-legume evergreens. Controlled environment results were then validated on a full-scale field embankment where contrasting species were established and soil hydro-mechanical responses monitored.[21] The species' ability to induce soil suction within the embankment, yields the same species ranking as in previous controlled-environment experiments. Indeed, the greatest suction values (70 kPa) along the embankment were consistently recorded in the plots vegetated with the evergreen legume *U. europaeus* (Fig. 15). This study clearly highlights the necessity to select different plant species to optimize the beneficial hydro-mechanical effect of the vegetation. Moreover, these field-scale measurements evidently show that for even low intensity rainfalls the soil suction may drop to zero, irrespectively of vegetation type and condition. This may result in a limited effect of vegetation on the soil suction when extreme rainfall events occur.[109,145,156,162,213]

7.2. Implementation of SVA interaction within engineering solutions from recent studies

This subsection presents scenarios from recent literature where *SVA* interaction has been considered and incorporated into the simulation of real case studies involving different geotechnical systems. While *SVA* interaction analyses have primarily been conducted to assess slope stability, the design and analysis of other geotechnical systems may also benefit from a more advanced implementation of *THM* processes, as discussed in previous chapters.

Building on the background provided above and considering the different levels of complexity in which a *SVA* analysis can be structured, Table 2 illustrates examples of geotechnical systems modelled and reported in the literature. In these cases, the effects of vegetation are analysed alongside other triggering factors, which vary depending on the type of loading (structural, environmental, seismic, etc.). Specifically, some key geotechnical systems are considered, including natural slopes, excavation/cut slopes, embankments, shallow embedded infrastructures, and the ground surface. The triggering factors examined include rainfall, earthquakes, deforestation, wildfires, erosion processes, and changes in land use (Table 2).

Table 2 also indicates the level of complexity of the *SVA* interaction analyses adopted in the studies. Although this summary is not exhaustive, it highlights the significant research opportunities that remain in this field and its potential for practical applications.

As reported in Table 2, the literature provides examples of the implementation of *SVA* interaction in the context of earthquake-induced failures in vegetated slopes. However, the study of *SVA* interactions under seismic conditions remains largely unexplored. This topic is of significant interest not only to the academic community but also to national and supranational agencies responsible for managing emergencies related to earthquake-induced landslides over large areas. Therefore, some aspects of this specific issue will be further discussed in

Table 2
Examples of geotechnical systems modelled at varying levels of complexity for SVA interaction modelling.

Geotechnical system	Triggering action	Mechanical M	Hydro-mechanical HM	Thermo-hydro-mechanical THM
Natural slopes	Rainfall	Murgia et al.[133]; Wu et al.[226]	Ni et al.[142]; Pedone et al.[150]	Guglielmi et al.[85]
	Erosion	Zhang et al.[236]	-	-
	Earthquake	Liang et al.[113,114]	Lann et al.[108]	-
	Deforestation / land use change	Kamchoom et al.[96]	Kamchoom et al.[96]; Mao et al.[125]	-
	Climate Change	-	Rianna et al.[161,163]; Comegna et al.[39]	-
	Wildfires	-	Abdollahi et al.[1]	Stasi et al.[183]
Excavation / Embankments	Rainfall	-	Tsiampousi et al.[204]; Sitarenios et al.[181]; Stirling et al.[184]; Pujević et al.[158]	An et al.[4]; Badakhshan et al.[11]
	Erosion	Sun et al.[187]	-	-
	Earthquake	-	-	-
	Deforestation / land use change	Kokutse et al.[103]	Tsiampousi [203]	-
	Climate Change	-	Rouainia et al.[166]; Tang et al.[198]	Zhang et al.[238]
	Wildfires	-	Abdollahi et al.[1]	-
Shallow embedded infrastructures/ Ground surface	Rainfall	-	Świtała et al.[188]; Xu et al.[228]	Hemmati et al.[87,88]; Rajeev et al.[160]; Ni et al.[139]; Wang et al.[216]; Samat[169]
	Erosion	-	-	-
	Earthquake	-	-	-
	Deforestation / land use change	-	Xu et al.[228]	-
	Climate Change	-	-	Jabbarzadeh et al.[92]; Tourchi et al.[202]
	Wildfires	-	-	-

the following final Section 8.

Furthermore, when incorporating *THM* processes related to *SVA* interaction into the design of geotechnical systems and structures, there is a growing need for guidelines and regulatory frameworks to support engineers in design practice. Such guidelines could further encourage the integration of vegetation-related *THM* processes into geotechnical design, ensuring that engineering interventions account for these interactions effectively.

In particular, these guidelines should also address the well-known uncertainties inherent in geotechnical design, which become even more critical when considering vegetation effects.

One possible strategy to tackle this challenge is the Reliability-Based Design (*RBD*) approach. In this respect, the uncertainties inherent to the geotechnical design when facing for instance the analysis of the static stability conditions of rooted soil slopes are generally dealt with by carried out simplified limit equilibrium approaches mainly accounting for the mechanical effect of roots through the increase in shear strength $\Delta\tau_r$ (Table 1) which is generally evaluated using simple semi-empirical equations. This issue is even more problematic concerning the seismic loading conditions, since scientific studies available in the literature are still far from giving well-established rules concerning the seismic behaviour of rooted slopes.

An example of the application of a *RBD* approach is briefly presented in the following subsection, focusing on the mechanical reinforcement provided by root systems within vegetated slopes incorporating the influence of uncertainties on the assessment of the slope factor of safety.

7.3. An example of reliability-based design for rooted slopes

RBD approaches generally adopt a simplified representation of the soil-roots interaction mechanism which fall within the basic level of complexity described in Chapter 3. In this framework, traditional deterministic methods deal with such uncertainties usually by employing conservative values to guarantee the design parameters and large safety factors. Nowadays, design codes incorporate a semi-probabilistic approach, rather than a deterministic one, considering uncertainties by applying partial factors on loads, resistances, and geotechnical parameters.

On the other hand, Reliability-Based Design (*RBD*) involves assessing the probability of failure using a target reliability index to evaluate safety margins. Probabilistic approaches and reliability analyses have gained widespread acceptance, enabling comprehensive evaluations of the impact of uncertainty on design parameters. Following these approaches, the slope probability of failure, P_f, can be expressed as:

$$P_f = \phi(-\beta)$$

This formulation associates P_f with the reliability index, β, introduced by Eurocode *EC0* as a measure of reliability. Here, ϕ denotes the cumulative distribution function of the standardised normal distribution. Introducing a performance function, g such that a structure is deemed stable when $g > 0$, the probability of failure is equivalent to:

$$P_f = Prob(g \leq 0)$$

For slope stability analyses, the performance function is identified as the factor of safety (*FS*). When the factor of safety is normally distributed, the reliability index β can be computed as follows:

$$\beta = \frac{\mu_{FS} - 1}{\sigma_{FS}}$$

where μ_{FS} and σ_{FS} are the mean value and standard deviation of *FS*, respectively. The reliability index quantifies the number of standard deviations separating the mean factor of safety from the critical value (*FS*=1). Different reliability levels correspond to consequence classes

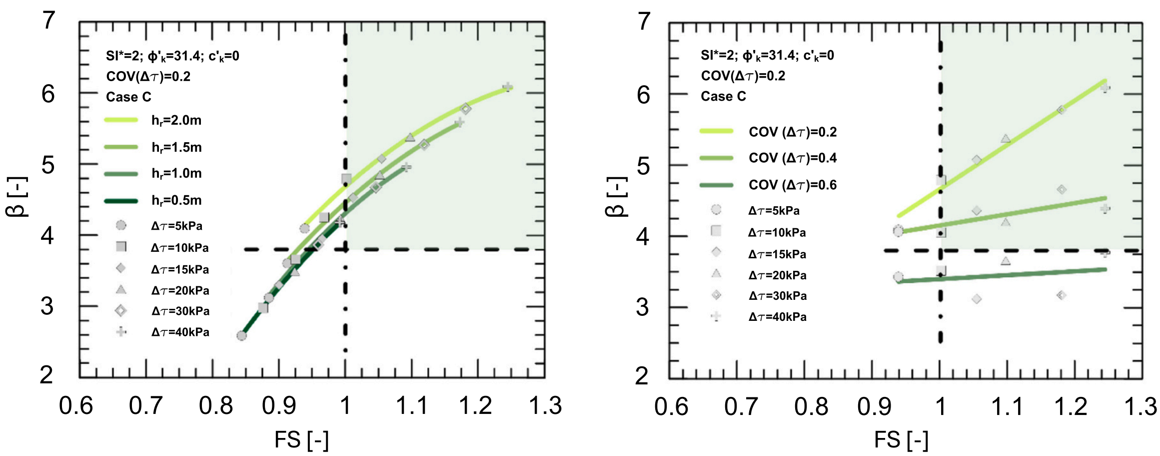

Fig. 16. Reliability index, β, *versus factor of safety, FS,* curves (reproduced from Pisano & Cardile[155]).

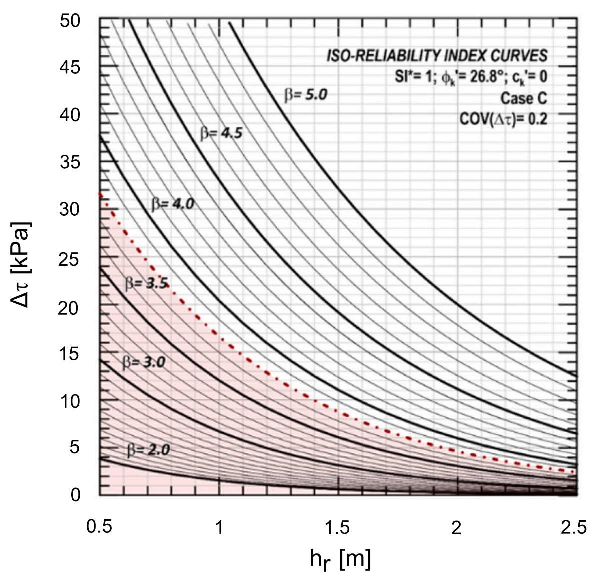

Fig. 17. Iso-reliability β-index curves (reproduced from Pisano & Cardile[155]).

(*CC*) and specific recommended minimum β values for the ultimate limit state (*ULS*). This methodology can assist in evaluating the effectiveness of deterministic approaches and Eurocode partial factors in consistently meeting safety and reliability criteria for vegetated slopes.[155] It considers variable parameters, such as root depth and root shear strength, in conjunction with geotechnical properties.

An illustrative example incorporating seismic actions is the study carried out by Pisano & Cardile[155] which includes 225 deterministic stability analyses employing *EC7* partial factors to determine if root reinforcement meets *EC7* safety criteria (*FS*=1). Subsequent probabilistic stability analyses (657 simulations) evaluate the reliability of slopes. Different configurations are analysed by varying the slope inclination angle (α), the soil friction angle (ϕ'), the root depth (h_r), and the root contribution to the soil shear strength ($\Delta\tau$). All selected slopes initially possess a stability index represented by $SI^*= 1$, corresponding to slopes devoid of vegetation under limit-equilibrium conditions. Subsequently, additional loads, such as seismic forces, are introduced to simulate real-world scenarios where collapse could occur, and vegetation might contribute to achieving a new safety condition. Seismic conditions are considered by applying a pseudo-static approach following the Bishop Method, which includes the evaluation of different seismic scenarios (case C is reported here) compared to a static scenario. Critical slip surfaces with depths less than 0.5 m are excluded, while the critical slip surface corresponding to the minimum factor of safety (*FS*) is identified. The study explores the variability of design parameters using the coefficient of variation (*COV*). Monte Carlo simulation assesses the impact of uncertainties on slope stability. The reliability index (β) is used to gauge how many standard deviations separate the mean factor of safety obtained from all the calculated safety factors. This index indicates the reliability of a specific slope configuration, with lower values indicating a higher degree of uncertainty. Fig. 16 illustrates the relationship between β and *FS* for various root depths and $\Delta\tau$ values, with thresholds marking regions meeting safety criteria. Results indicate compliance with deterministic analysis when data uncertainty is low ($COV(\Delta\tau)$= 20 %). High *COV* percentages result in reliability values falling short of the targeted index, highlighting limitations in deterministic partial factors. Multiple regression analyses are then performed on the collected data, leading to the development of iso-reliability charts. These charts can assist in selecting the appropriate h_r- $\Delta\tau$ combinations to achieve the desired level of reliability.

Fig. 17 illustrates an example of iso-reliability curves obtained for one of the investigated slope configurations and the worst-case seismic scenario, with a $COV(\Delta\tau)$ of 20 %.

A further example is the implementation of probabilistic approaches and reliability analyses as it was done in the web-application SlideforNET.[38] In particular, this web application allows to take into account the uncertainties related to the three-dimensional distribution of root systems of different species that determine a corresponding root mechanical reinforcement distribution.[210,38]

8. The assessment of seismic performance of rooted slopes

If the earthquake effects are introduced in the analyses devoted to the assessment of the stability conditions and of the post-seismic performance of vegetated slopes, the level of complexity further increases since the behaviour of soils and roots under cyclic and dynamic loading conditions and their complex dynamic interaction mechanisms are to be considered. Also, the inertial effects arising in the shallowest soil masses potentially involved in the earthquake-induced plastic mechanisms must be considered. Finally, the analysis of the seismic loading conditions need to account for all the aspects which typically characterize problems of soil dynamic with high strain rate: (*i*) the possible coupling between the frequency content of the earthquake-induced ground motion and the vibration frequencies of rooted soil slope; (*ii*) the effect of the drainage conditions which could imply change in the pore pressure that, under partial saturation conditions, could start to dissipated during the ground motion.

Despite these relevant complexities inherently concerned with the analyses of such phenomena, this topic received great attention in the last years due to its relevance from a geotechnical engineering point of

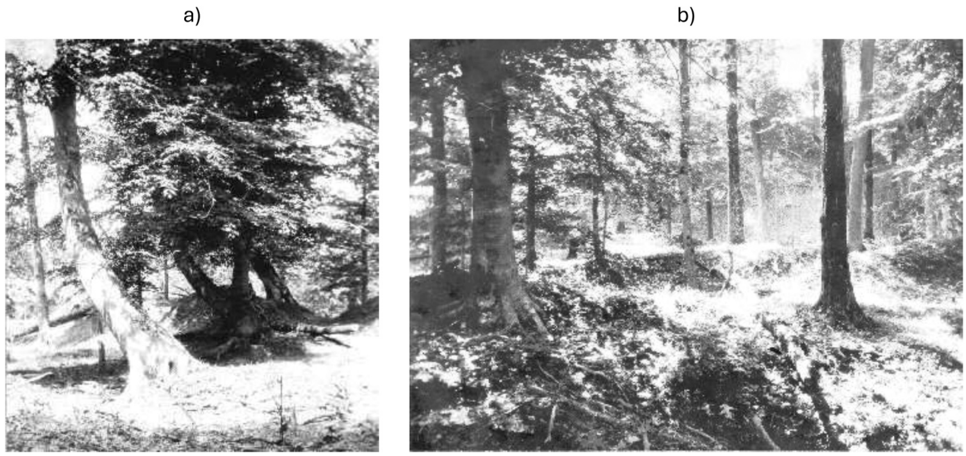

Fig. 18. Effects of the 1811–12 New Madrid earthquakes: a) trees tilted by the earthquake, Chickasaw bluffs east side of Reelfoot Lake (note twist of trees into upright position); b) Landslide scarps in Chickasaw Bluffs, east of Reelfoot Lake (USGS, public domain).

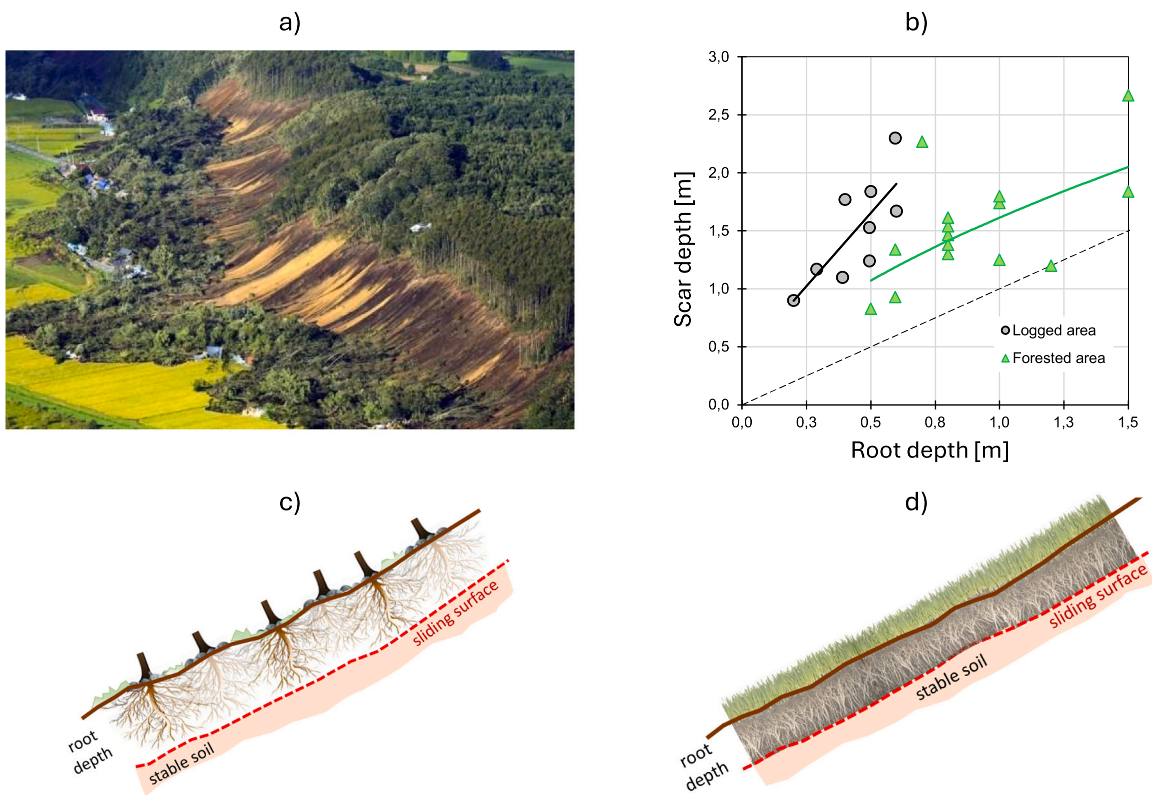

Fig. 19. Effects of the 2018 Hokkaido Earthquake on vegetated soil slopes: a) typical ridge landslides observed after the event (source American Geophysical Union); b) relationship between the average depth of failure surface and average root depth observed in forested (c) and logged (d) areas (data from Ritonga et al.[165]).

view. Vegetation can significantly affect the stability and performance of the shallowest portion of natural slopes in terms of activation of plastic mechanisms, associated shallow slip movements and magnitude of the corresponding permanent displacements.

The research activities on this topic are still in progress and include experimental tests and numerical analyses carried out at different scale; these range from the small scale of rooted soil specimens (subjected to laboratory investigations), to reduced scale physical models of rooted slopes (generally tested in dynamic centrifuge[135]) and, finally, to numerical analyses of full-scale problems (e.g.,[113,114]). Data available in the literature are still far from giving well-established rules concerning the seismic behaviour of rooted slopes and, thus, pseudo-static approaches and Newmark-type analyses are generally adopted to predict the seismic stability conditions and post-seismic serviceability of rooted soil slopes.

In this vein, and with the intent of giving useful insight into the behaviour of rooted slopes during and after very large seismic events, the following sub-sections tries to summarize some relevant field data derived from post-seismic surveys.

8.1. Deepening of seismic-induced plastic mechanisms and energy dissipation

Probably, the first well-documented case-histories related to the relationship between earthquakes and vegetated soils are those concerned with the 1811–1812 New Madrid earthquakes, a series of intense intraplate earthquakes occurred in the U.S.A. at the beginning of eighteenth century (from December 1811 to February 1812) with very large moment magnitude ranging between 7.2 and 8.2.[76] At that time, post-seismic surveys mainly focused on the effect of the earthquake on vegetated soil while the effect of vegetation on the seismic performance of rooted slopes was not sufficiently investigated. However, the few data relative to this seismic event highlighted the effects of roots on the earthquake-induced phenomena. Because of the event, tilted and or twisted trees (Fig. 18a) were observed in several areas of the epicentral zone and the effect of roots on the location and on the extension of the earthquake-induced ("e-i" in the following) slips were firstly documented (Fig. 18b).

Larger set of data were nowadays available also with reference to more recent large earthquakes. The consequences of the 2018 M_w= 6.7 Hokkaido Eastern Iburi earthquake (occurred in the Hokkaido Island, north of Japan) allowed to detect some common features of the "e-i" shallow slides typically induced in vegetated slopes (e.g.[106,165]). This seismic event triggered many landslides which may be classified as shallow slides mainly characterized by planar failure mechanisms; in most of the cases, uprooted trees densely accumulated at the foot or near the toe of the landslide were detected after the event (Fig. 19a).

In the areas where large landslides did not occur, most of post-seismic reports pointed out the relevant influence of root systems confirming, also for the seismic loading conditions, the importance of the soil-root interaction mechanism and the relevance of the confining and reinforcing effects (*M*, see Table 1). During the earthquake-induced ground motions this led to an improvement of the mechanical behaviour of the shallowest soils avoiding or limiting plastic mechanisms and reducing the magnitude of the associated large permanent displacements. In some cases, during the post-seismic surveys sliding surfaces associated to the observed slip movements have been detected being always at depths greater than those affected by the roots; as an example, Fig. 18b provides the relationship between the root depth and the average depth of the sliding plane (denoted as siding surface in Fig. 19b) obtained using the data by Ritonga et al.[165] relative to both forested (Fig. 19c) and logged (Fig. 19d) areas stroked by the 2018 M_w= 6.7 Hokkaido Eastern Iburi Earthquake; in Fig. 18b the best fits of the two set of data are also plotted and it apparent that the sliding surface is always deeper than roots. This outcome points out that during the ground motion shear strain generally localizes in the deeper unrooted soils.

The deepening of the sliding surfaces associated to the presence of the roots, represents a relevant characteristic of the seismic performance of rooted slopes and implies larger plastic volumes involved in the seismic-induced failure mechanisms and, thus, larger dissipation of the energy associated to the earthquake-induced ground motion. This beneficial energy dissipation led to an improved seismic response of the shallowest portion of rooted soil slopes and justify the cases in which no failure mechanisms were observed even in the case of severe earthquakes.

Table 3
Some large seismic event for which data on the seismic behaviour of vegetated slopes have been collected.

Earthquake	M_w	References
1811–1812 New Madrid (USA)	7.2–8.2	Fuller[76]
1976 Songpan County (China)	7.3	Allen et al.[2]
1998 Taumarunui (New Zealand)	6.7	Shou et al.[179,178]
1999 Taiwan	7.7	Saba et al.[168]
2005 Kashmir (Pakistan)	7.6	Saba et al.[168]; Khan et al.[98]
2008 Wenchuan (China)	7.9	Yang et al.[230]; Huang and Li[91]; Zhang et al.[239]; Fan et al.[64]
2018 Hokkaido Eastern Iburi (Japan)	6.7	Konagai & Nakata[106]; Ritonga et al.[165]

8.2. Post-seismic data: landslides frequency and recovery time

Large sets of the data are also available in the literature with reference to the post-seismic behaviour of vegetated slopes. Table 3 lists some of these events together with the corresponding values of the moment magnitude M_w and some relevant references. The data provided in these studies (Table 3) are relative to both short- and long-term periods, meaning after the main shock and several years after the earthquake, respectively.

The observed seismic and post-seismic performances have been examined by comparing the characteristics of the observed failure mechanisms, topography and vegetation data in the stroked area, landslides occurrence and their frequency before and after the event. The analyses of these large sets of data required a multidisciplinary investigating effort which allowed us to detect some noteworthy common features of these phenomena. Herein, some of them are described focusing the attention on those relevant from a geotechnical point of view.

The collected data firstly confirm that the large soil movements associated to the landslides triggered by earthquakes produce widespread vegetation damage and affect the soil processes and roots biomasses with relevant consequences on the root development and on the increase of their mortality. As an example, for most of the earthquakes listed in Table 3 the vegetation mortality significantly increased in the 5–7 years after the event. Most of the collected data also confirm that, accordingly, stroked areas became more prone to secondary disasters such as mountain floods, debris flow and landslides. Specifically, the data pointed out that the post-seismic landslides susceptibility depends not only on the vegetation typology and local topography but also on the extension of the sub-area where vegetation was damaged by the earthquake (being the area where probably an increase in roots mortality occurred after the earthquake).

After the earthquake, natural (or man-made) vegetation recovery began playing a crucial role since it affects the hydrological properties of the landslide surfaces, the hydraulic and mechanical interaction between the new roots and surrounding soils. Thus, the revegetation process is crucial for the landslide activities and frequency in the stroked areas and is also relevant to the damages induced by future rainfalls and earthquakes.

Concerning the landslide frequency, most of the data available in the literature clearly show that it significantly increases immediately after major earthquakes and then decreases with time. Specifically, in the short term (i.e. after the main shock) the increase in landslides frequency is mainly related to the effect of the aftershocks which may trigger or reactive landslides in the area where the vegetation was destroyed by the earthquake; in the long term the collected data suggest an increase of landslides frequency (in comparison with the pre-earthquake period) as a consequence of the increased vulnerability of the stroked area were the number of rain-induced landslides generally also increases. With time, the landslides frequency reduces, and a sort of recovery time can be evaluated, representing the time required for landslide activity/frequency coming back to the values previous the earthquake. According to the evidence, the relevance of this recovery time with reference to the damages potentially induced by future earthquakes is apparent.

As a final example, during the 2008 M_w= 7.9 Wenchuan earthquake massive landslides caused widespread vegetation damage (about 1.160 km^2 were damaged within an area of about 111.000 km^2), leading to significant changes in vegetation cover; in the short term (following the main shock), due to the abundant loose debris and rainfalls, frequent post-seismic debris flows and landslides (mainly re-sliding) have been reported in the Wenchuan region[230]; in the long-term the earthquake is thought to have had (long-term) impacts on post-seismic landslide frequencies.[91,239]

All these findings reported in this chapter highlight the crucial role of vegetation in modifying seismic-induced failure mechanisms and post-seismic recovery, confirming the need for an integrated, interdisciplinary approach to better understand and predict the complex processes governing the stability of vegetated slopes also under dynamic loadings.

9. Conclusions

In recent years, the study of Soil-Vegetation-Atmosphere (*SVA*) interaction has gained increasing attention due to its crucial role in geotechnical engineering and environmental sustainability. The complexity of this interaction stems from the coupled thermo-hydro-mechanical (*THM*) processes that govern mass and energy exchanges between the atmosphere and soil through the vegetation layer. Understanding and modelling these mechanisms is essential for assessing the stability and performance of geotechnical systems subjected to both static and dynamic loads, as well as evolving environmental conditions.

This paper has aimed to provide an interdisciplinary perspective by integrating contributions from geotechnical engineering, agronomy, forest science, and soil-bioengineering. The study has explored SVA mechanisms at multiple scales, following a structured approach that progresses from basic soil-root mechanical (*M*) interactions to more complex soil-root-water (*HM*) towards full *THM* coupling. Through a combination of laboratory experiments, physical modelling, and advanced numerical simulations, this contribution has sought to highlight the fundamental processes involved in *SVA* interactions and their implications for geotechnical design and risk assessment.

Despite the significant progress made in recent decades, key research gaps remain. One of the primary challenges is the need for a more integrated and standardized approach that bridges the diverse methodologies used across disciplines. Future research should focus on improving the consistency of experimental procedures, data interpretation, and modelling techniques to enhance comparability between studies. Additionally, while various studies have investigated the short-term impacts of vegetation on soil properties, long-term monitoring of vegetated slopes and engineered systems remains limited. Understanding the temporal evolution of soil-vegetation interactions, particularly under changing climatic conditions, is relevant for predicting their long-term performance and resilience.

Another critical area for further investigation is the post-seismic behaviour of vegetated slopes and geotechnical structures. While vegetation is often considered beneficial for slope stability, its role in post-earthquake conditions remains poorly understood. Research should aim to quantify the effects of root reinforcement and hydrological changes following seismic events to better inform mitigation strategies. Furthermore, given the increasing frequency of extreme weather events, studies should explore the response of vegetated geotechnical systems to prolonged droughts, intense rainfall, wildfire occurrence, and seasonal variations in temperature and moisture content.

From a modelling perspective, future advancements should focus on refining coupled numerical models that can accurately capture the nonlinear and time-dependent nature of *SVA* interactions. The development of multi-scale models that integrate laboratory findings with field-scale observations would provide a more comprehensive understanding of how vegetation influences geotechnical stability in real-world scenarios. Additionally, incorporating machine learning and data-driven approaches could enhance predictive capabilities, offering more reliable tools for risk assessment and engineering design.

In conclusion, while substantial advancements have been made in understanding *SVA* interactions, addressing the remaining challenges requires a concerted effort to integrate experimental, analytical, and numerical approaches across disciplines. By fostering collaboration between researchers in geotechnical engineering, ecology, and atmospheric sciences, the knowledge and modelling capabilities within this field can increase and pursue toward more holistic and sustainable solutions for geotechnical problems in both natural and engineered environments. Strengthening this interdisciplinary framework will not only advance scientific knowledge but also contribute to the development of more resilient and adaptive geotechnical systems in the face of evolving environmental and climatic challenges.

CRediT authorship contribution statement

Manuela Cecconi: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Formal analysis, Conceptualization, Supervision, Project administration. **Vito Tagarelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Formal analysis, Conceptualization, Supervision, Project administration. **Federica Cotecchia:** Writing – review & editing , Methodology, Conceptualization, Project administration. **Vincenzo Pane:** Conceptualization, Project administration. **Floriana Anselmucci:** Writing – original draft, Investigation. **Ilaria Bertolini:** Writing – original draft, Investigation. **Giovanni Biondi:** Writing – original draft, Writing – review & editing, Investigation. **David Boldrin:** Writing – original draft, Investigation. **Vittoria Capobianco:** Writing – original draft, Writing – review & editing, Investigation. **Giuseppe Cardile:** Writing – original draft, Writing – review & editing, Investigation. **Sabatino Cuomo:** Writing – original draft, Investigation. **Pantaleone De Vita:** Writing – original draft, Investigation. **Alessandro Fraccica:** Writing – original draft, Writing – review & editing, Investigation. **Gerrit Meijer:** Writing – original draft, Investigation. **Luca Pagano:** Writing – original draft, Investigation. **Marianna Pirone:** Writing – original draft, Writing – review & editing, Investigation. **Massimiliano Schwarz:** Writing – original draft, Investigation. **Alessandro Tarantino:** Writing – original draft, Investigation. **Jean Vaunat:** Writing – original draft, Formal analysis. **Anil Yildiz:** Writing – original draft, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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