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*Landslides in terraced cultural landscapes of the Mediterranean area:
influence of agricultural practices and dry-stone walls' efficiency on landslide hazard*

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ABSTRACT

The terraced cultural landscape of the Cinque Terre has experienced a marked acceleration in geo-hydrological instability phenomena over the last decades. This critical trend is attributed to a synergistic convergence of two primary factors: changes in the pluviometric regime, directly correlated with climate change, and the abandonment of traditional cultivation practices, which historically concurred to the balance between human activity and geomorphological slope processes. The resulting instability, which manifests as both large-scale collapses and localised failures of the dry-stone wall terrace systems, not only compromises land safety but also threatens the integrity of the landscape, which is recognised by UNESCO as a World Heritage Site.

The stability of the terraced slopes of the Cinque Terre has been the subject of numerous scientific studies, which have mainly investigated the factors influencing the triggering of rainfall-induced shallow landslides at the basin scale. While these contributions have broadened knowledge on the resilience of these human-modified slopes using innovative methodologies for susceptibility assessment and post-event analysis, they highlighted a persistent gap in the literature. Specifically, there is a lack of studies that have analysed in detail and quantitatively the interrelationships between hydrological conditions, land use, and other influencing factors. A deep understanding of these dynamics is essential for accurately defining the factors driving slope instability and for developing effective and targeted mitigation strategies, which are crucial for counteracting the progressive degradation of this invaluable cultural landscape.

To this end, the present study, using data retrieved from the "Stone Wall for Life" project's activities, aims at filling this gap by adopting a quantitative multi-scale approach to investigate the factors and conditions that influence the terraced slope stability, with a specific focus on the role of vegetation. The multi-scale methodological approach involved numerical modelling conducted on three experimental sites that exhibit varying land-use conditions (i.e., cultivated and abandoned scenarios). The study involved a preliminary stability analysis aimed at quantifying the influence of slope-scale stability factors through a shear strength reduction analysis. This preliminary analysis identified the characteristics of the material at the dry-stone wall foundation as an important controlling factor of the slope stability. Subsequently, the research proceeded towards a detailed local-scale investigation, focused on individual dry-stone wall terrace systems. To construct robust numerical models, in-situ hydrological and mechanical monitoring data collected in the frame of the "Stone Wall for Life" project were used. The models enabled flow analyses, stability analyses, and notably, coupled flow-

deformation analyses. The flow analyses, integrated with stability analysis, allowed for the validation of the hydrological model and the definition of the factors regulating dry-stone wall stability and their relationship with the phases of the hydrological cycle (i.e. drying and wetting phases). The coupled flow-deformation analysis was fundamental for the validation of the mechanical model, enabling the comparison between numerically simulated horizontal stresses acting on dry-stone wall and those recorded in situ. This validation was essential for investigating the role of vegetation in terms of compressive stress regime that develops at the interface between the dry-stone wall and the backfill. The innovative aspect of this work lies in the analysis of the contribution of vegetation to soil stability, which was modelled exclusively through the increase in soil resistance produced by suction generated by plant roots following evapotranspiration process. The obtained results provided useful contributes for the definition of evidence-based landslide risk mitigation strategies.

CHAPTER 1 – INTRODUCTION

1.2 STATE OF THE ART

Climate change is redefining geohydrological dynamics in many coastal regions, and the Cinque Terre (NW Italy) is no exception. Indeed, in recent decades, there has been a gradual increase in global precipitation and temperatures (Climate Data, 2021; Dastgerdi et al., 2022), leading to a higher frequency of flooding, landslides, and soil erosion events (Seneviratne et al., 2012; Watts et al., 2021). Such events exemplify the stability problem of the terraced structures that dominate the UNESCO landscape of the Cinque Terre, a century-Old Testament to the invaluable relationship of coexistence between humans and the environment.

Therefore, this paragraph aims to explore the state of the art of studies focused on understanding and mitigating the impacts of these phenomena on the territory, analysing the most innovative investigation methodologies.

Recent variations in rainfall patterns and their impact on the Cinque Terre region have been the subject of in-depth scientific investigations, particularly following the extreme rainfall event occurred on October 25, 2011. This event, which affected eastern Liguria and northern Tuscany, recorded exceptional cumulative precipitation (up to 539 mm/24 h at Brugnato and 382 mm/24 h at Monterosso al Mare), characterized by an estimated return period exceeding 100 years (Cevasco et al., 2013; D'Amato et al., 2013, Brandolini et al., 2018). The event triggered thousands of shallow landslides, widespread erosional and depositional processes, and numerous flash floods. The consequences were catastrophic, resulting in 13 fatalities, the evacuation of approximately 1200 people, and severe infrastructural damage (Cevasco et al., 2013).

In response to these extreme instability events, numerous studies have been conducted with the aim of identifying areas susceptible to slope instability and developing susceptibility maps to delineate potential instability zones and implement mitigation strategies (Brandolini et al., 2014; Schilirò et al., 2018; Raso et al., 2018, 2020; Di Napoli et al., 2020; Raimondi et al., 2020).

In this context, Raso et al. (2019) proposed a detailed landslide inventory for the Cinque Terre area. This study quantified the extent of slope instability processes, providing a fundamental basis for adopting effective mitigation strategies. The authors identified a total of 405 landslides, predominantly classified as debris slides (33.3%), which often represent the main cause of instability for dry-stone walls. Other significant phenomena included rockfalls (18.5%)

and debris flows (12.6%), predominantly observed in the western sector of the Cinque Terre, between the municipalities of Monterosso and Vernazza (Figure 1.1).

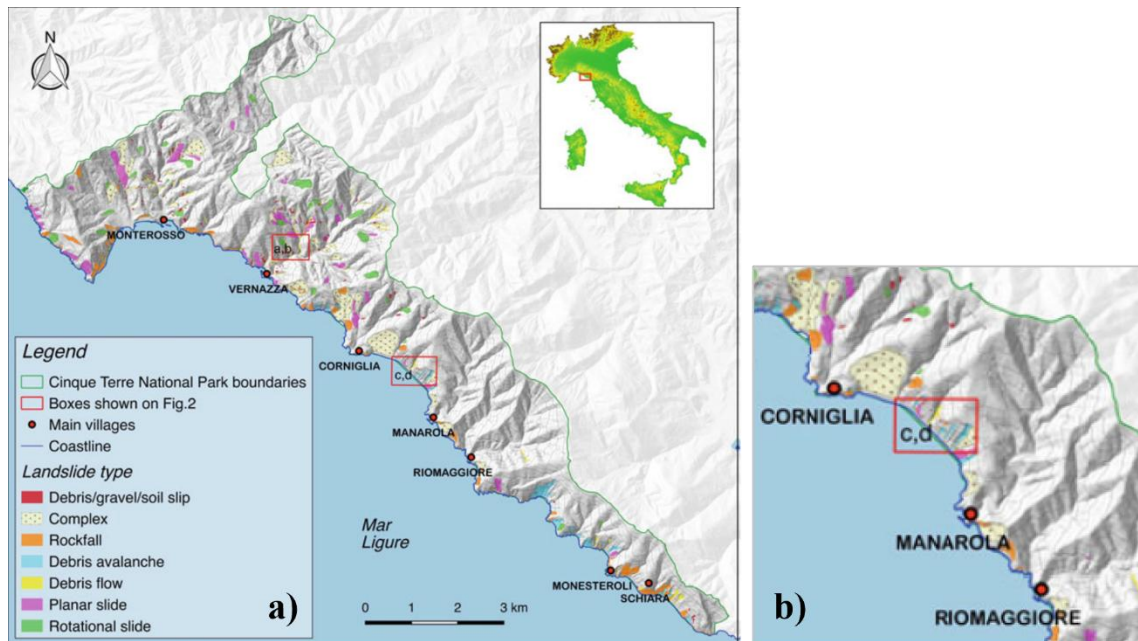


Figure 1.1 - a) Landslide inventory map of the Cinque Terre National Park. b) Landslide distribution in the Manarola area (from Raso et al., 2018).

Several studies (Cevasco et al., 2014; Schilirò et al. 2018, Raso et al., 2018) revealed that the extreme rainfall event of October 25, 2011, triggered a wide range of landslide phenomena in the Cinque Terre area, especially in the territory belonging to the Vernazza and Monterosso al Mare municipalities. It is important to emphasize, however, that this event did not directly affect the Manarola area with new instability detachments. In fact, the instabilities identified and mapped in the Manarola area, as highlighted by Di Napoli et al. (2021), predate the October 25, 2011, event. Furthermore, these same instabilities are exclusively concentrated along the coastal strip, with no significant instability phenomena observed in the inner areas (Figure 1.1). Parallel to this, the study conducted by Di Napoli et al. (2020) significantly advanced the understanding of the potential distribution of landslide phenomena across the entire Cinque Terre area. The authors developed a landslide susceptibility map using the Ensemble Modelling methodology. This innovative approach integrates predictions generated by multiple Machine Learning algorithms, optimizing the model's predictive accuracy.

Through these detailed analyses, the authors demonstrated that coastal areas are the most exposed to potential geomorphological instability, where high steep slopes represent a primary predisposing factor (Figure 1.2). Moreover, susceptibility was also found primarily correlated

to other two predisposing factors: namely the abandonment of traditional dry-stone wall terraces and the obstruction of drainage channels. These conditions are often a direct consequence of the abandonment of traditional agricultural practices and the subsequent degradation of the land, highlighting the complex relationship between natural and anthropogenic factors in the dynamics of instability.

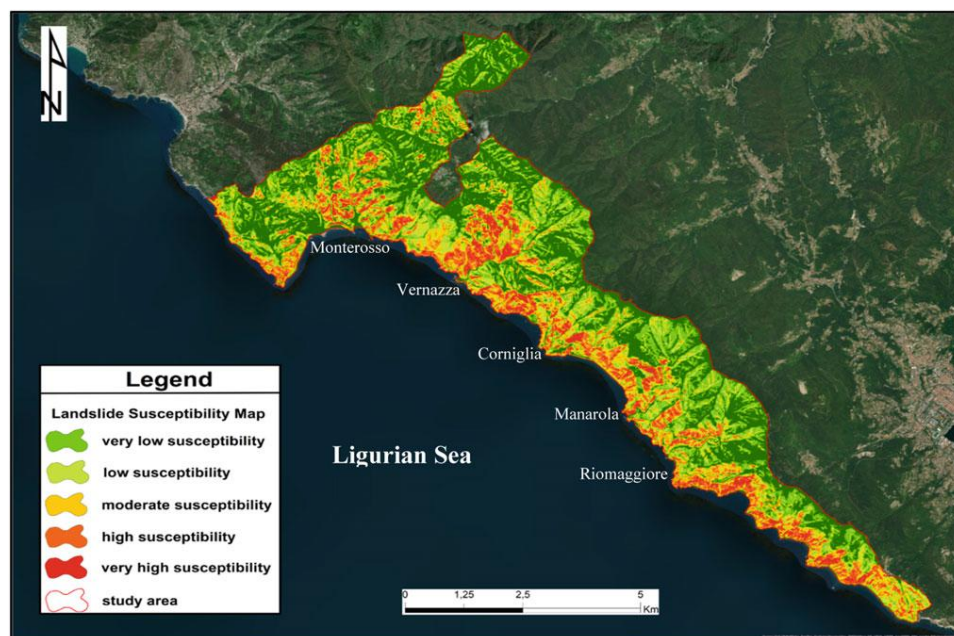


Figure 1.2 - Landslide susceptibility map of Cinque Terre National Park (from Di Napoli et al., 2020).

The comparison between the data presented by Di Napoli et al. (2020) and the prior observations of Raso et al. (2018) clearly outlines the territory susceptibility to instability. Coastal areas unequivocally exhibit a high vulnerability to instability phenomena, with evidence of detachment episodes occurring even in recent times.

Regarding the internal areas, the study by Raso et al. (2018) confirmed that these zones were not affected by new detachment events during the last phenomenon analysed. Despite this apparent recent stability, Di Napoli et al. (2020) nonetheless classify the internal areas as zones with high susceptibility to landslide initiation. In this context, the primary predisposing factors increasing their vulnerability are predominantly linked to anthropic activity.

Concerning this, numerous studies have investigated the factors predisposing to instability in this peculiar slope morphology, identifying the abandonment of agricultural terraced slopes as one of the primary contributors to instability. Before analysing the problems arising from such abandonment, it is crucial to understand the reasons that led to their construction and development.

Agricultural terracing techniques are rooted in ancient times and developed independently in various geographical areas in response to the need to cultivate lands characterized by steep slopes. The primary objective of such systems was twofold: to create flat surfaces on slopes to extend cultivable areas and, concurrently, to promote increased water infiltration and a significant reduction in soil erosion processes caused by surface runoff.

Despite their numerous benefits in terms of agricultural production and soil conservation, terraced slopes require constant and intensive high-effort maintenance. Precisely, because of the demanding nature and low mechanization of these agricultural systems, beginning after World War I and definitively after World War II, the development and promotion of industrial activities led to a progressive abandonment of agriculture, which was particularly pronounced in these steep areas (Tarolli et al., 2019).

The abandonment of these practices now represents one of the primary causes of the deterioration of terraced structures and the consequent increase in landslide risk.

Initial studies on the influence of terrace abandonment on slope stability in the Cinque Terre area began in 1989 with the work of Carl & Richter (1989). Specifically, this work qualitatively identified the gradual process of slope abandonment, particularly from the perspective of natural vegetation growth and its related influence on hydrological and stability conditions. The authors stated that the onset of the abandonment process leads to a predictable vegetative succession that develops over approximately 60 years. According to the study, the landscape is initially covered by grass and herbaceous plants, followed by denser shrubs such as brambles and ferns, eventually progressing to pioneer tree formations like holm oaks and pines during the most advanced stages.

According to the authors, these vegetation changes are not merely an aesthetic transformation but profoundly alter the soil's water regime. Abandoned terraces progressively lose their water storage capacity, leading to a decrease in soil moisture content and a reduction in the potential infiltration rate. Consequently, effective rainfall significantly diminishes, and the soil, sometimes compacting due to the accumulation of fine particles and clay, becomes less capable of retaining water, increasing the risk of runoff, with a direct consequence on dry-stone wall collapses. These collapses are primarily linked to deteriorated drainage systems resulting from the abandonment process and runoff from the upper parts of the slope, which generates an increase in soil pressure behind the wall. It has been observed that wall collapses increase significantly with the duration of abandonment.

Following these initial qualitative observations, the more recent work by Brandolini et al. (2018) provided a detailed and quantitative analysis of the landslide dynamics that affected the

municipality of Vernazza in October 2011. This study specifically investigated the response of terraced slopes to intense rainfall, focusing on the relationship with land abandonment by quantifying the volumes of mobilized debris during the event.

Through a comparative investigation based on pre- and post-event LiDAR data and aerial photographs, the authors demonstrated that abandoned terraced slopes mostly contributed to the total quantity of debris. They found that 87,000 m³ of debris was detached by shallow landslides from a terraced areas of approximately 2.8 km²; the largest debris volumes (60.6% of the total eroded volumes, namely 52,000 m³) originated from abandoned terraces with dense vegetation cover (ATD). A further significant portion, namely 28.5% (approximately 24,800 m³), was mobilised from abandoned terraces with sparse vegetation cover (ATP).

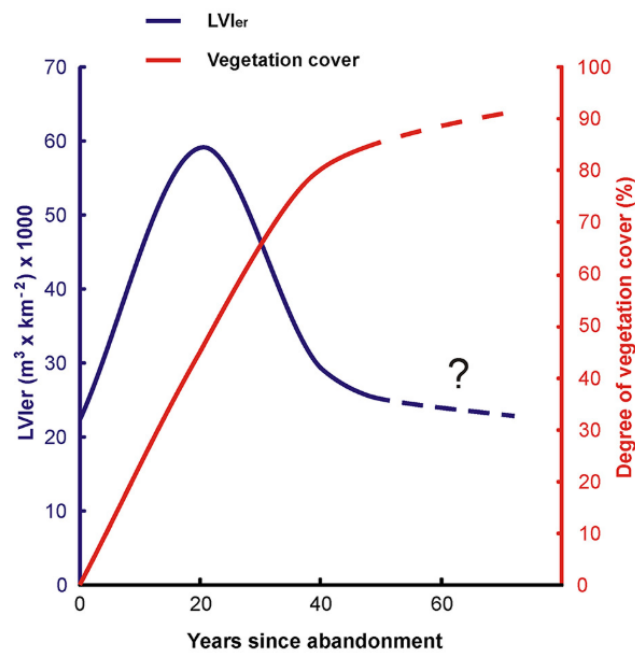


Figure 1.3 - Relationships between time of terrace abandonment (years), slope degradation (landslide volumetric index—LVler) and vegetation growth (%) (from Brandolini et al., 2018).

Furthermore, the authors asserted that terraces abandoned for a relatively short period (less than 25-30 years), classified as ATP, represent the most critical land-use class in terms of hazard. Indeed, these areas exhibited erosion rates approximately 2-3 times higher than both long-term abandoned terraces (ATD, over 25-30 years) and still-cultivated terraces (CT) (Figure 1.3). This finding suggests that the period that elapses between land abandonment and the significant establishment of a stable natural vegetation cover could represent the phase of greatest vulnerability for the stability of terraced areas.

The research problems concerning the influence of land use on landslide initiation in the Cinque Terre area has been further investigated by subsequent studies, including those conducted by

Cevasco et al. (2013), Schilirò et al. (2017), Agnoletti et al. (2019), and Pepe et al. (2019). These studies have consistently highlighted a higher incidence of shallow landslide events in abandoned areas. Such observations reinforce the hypothesis that the abandonment of land management practices and the consequent uncontrolled vegetation development can significantly contribute to an increased vulnerability of the terraced landscape to landslides risk. Some of the main results of these studies are summarized in Figure 1.4.

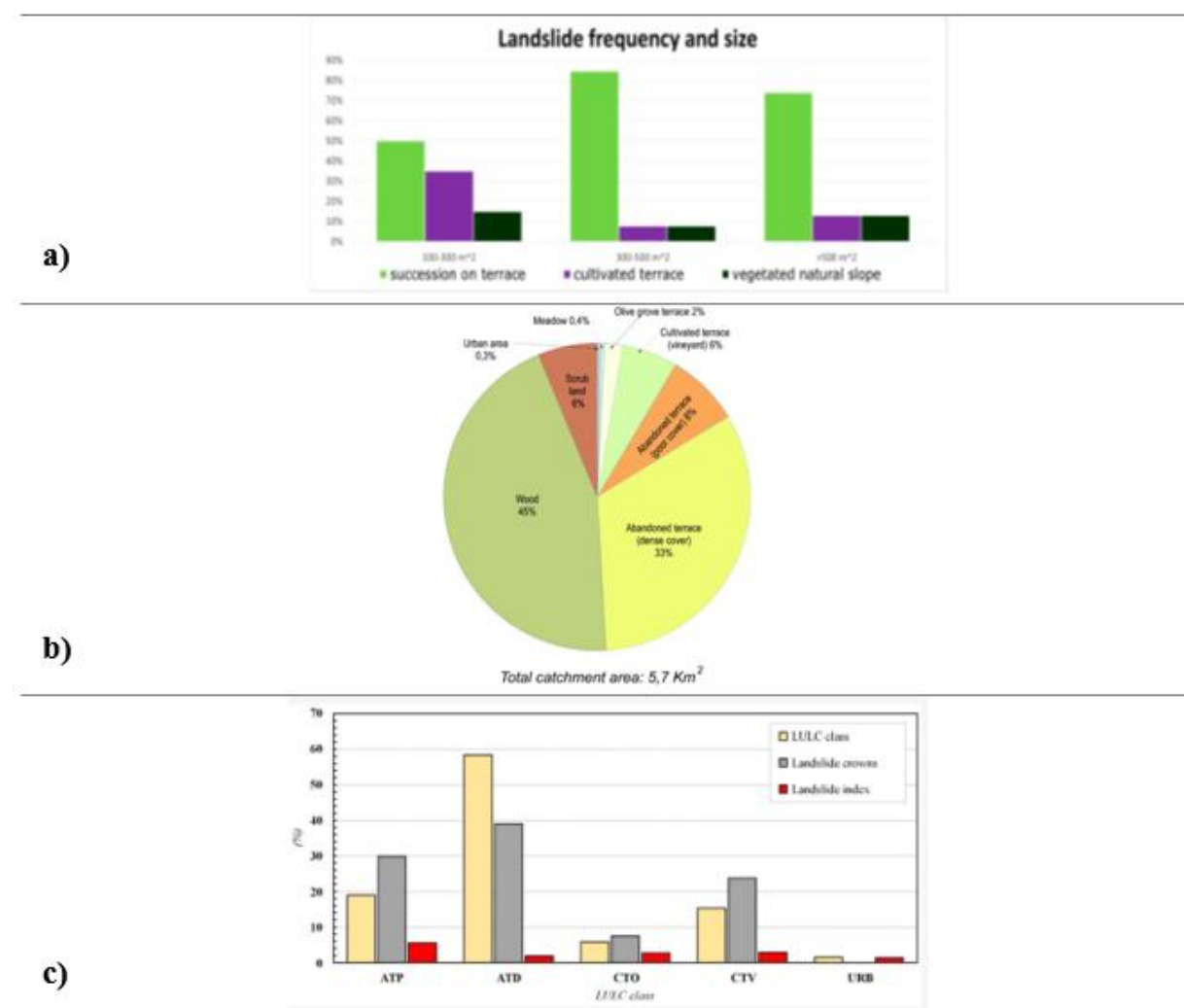


Figure 1.4 - Landslide frequency distribution in relation to land use: a) from Agnoletti et al., (2019), the category “succession on terrace”, is composed by both wood and shrub cover; b) from Cevasco et al., (2013); c) Pepe et al., (2019).

Further investigations by Cevasco et al. (2014), based on the analysis of landslide events that occurred on October 25, 2011, explored the predisposing factors influencing the initiation of these phenomena, such as bedrock lithology. Specifically, the impermeable clay complex (i.e., made up mainly of shales and limestones) showed a landslide percentage of 43,3%, while the more permeable lithologies (i.e., mainly fine-grained sandstones) showed a slightly higher

landslide percentage of 47,7%. However, the authors asserted that the most significant factor influencing slope stability was land use (Figure 1.5).

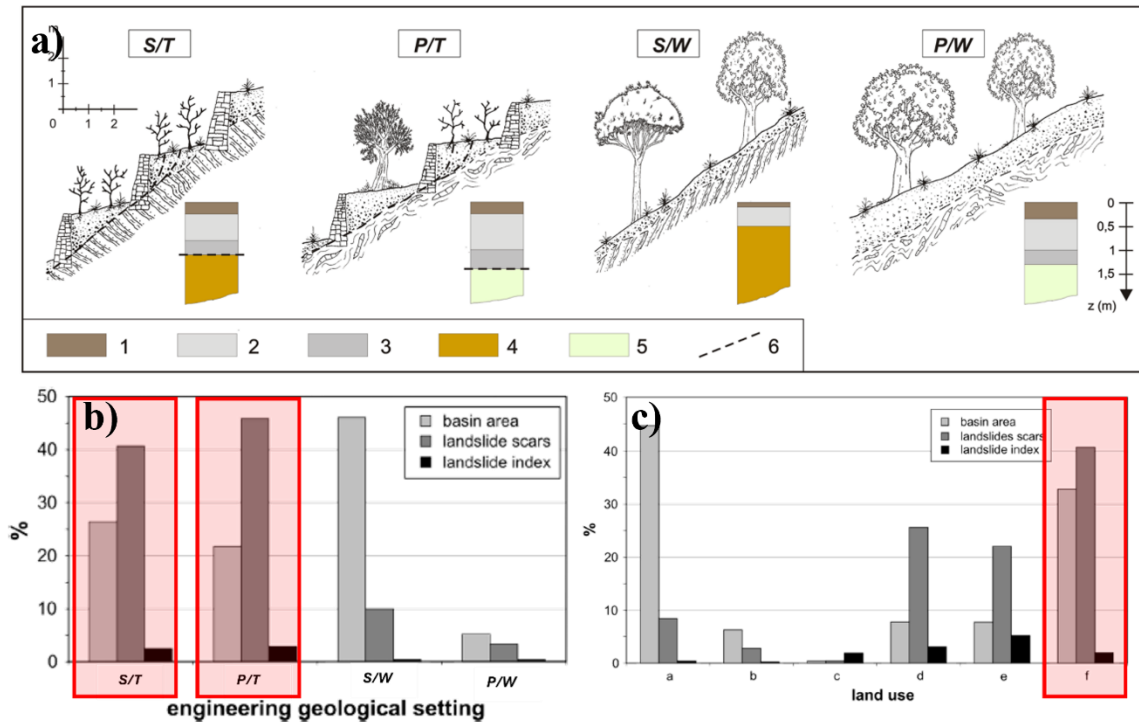


Figure 1.5 - a) Stratigraphic and geotechnical models related to engineering- geological units. The letters S and P refer to the type of substrate (arenaceous and pelitic), while T and W indicate the type of land use (terraced and woodland). 1-humus; 2-loose eluvial-colluvial deposits; 3-dense eluvial-colluvial deposits; 4-predominantly sandstone bedrock; 5 predominantly pelitic bedrock; 6-initial failure surface b) istribution of landslides in relation to geological setting and c) land use (from Cevasco et al., 2014).

The problem of agricultural terraced slope degradation following the abandonment of traditional agricultural practices is not peculiar to the Cinque Terre area but represents a widely recognised and studied challenge globally. Numerous studies conducted in diverse geographical contexts have investigated the consequences of terraced slope abandonment on their stability, highlighting recurrent and generalisable issues.

Multiple research efforts, including those by Llorens et al. (1992), Harden et al. (1996), Díaz et al. (2007), Lesschen et al. (2008), Stanchi et al. (2012), and Moreno et al. (2019), while analysing specific geographical contexts, converge in demonstrating how the cessation of terrace maintenance leads to significant soil degradation and a marked increase in erosive processes. According to the authors, such degradation develops through the deterioration of dry-stone wall structures, obstruction of drainage systems, and alterations to the vegetative

cover, factors which compromise the stability of the slopes and increase their vulnerability to landslides and erosion.

These studies did not merely observe the problem but also identified the specific degradation mechanisms that are activated. For instance, in 1996, Harden et al. (1996) demonstrated that runoff and erosion rates on abandoned land in the Ecuadorian Andes are significantly higher than on cultivated land. This observation aligns with subsequent studies that quantified the intensity of the problem.

Subsequently, in 2007, Díaz et al. (2007) identified piping erosion (or tunnel erosion) as the primary instability phenomenon on terraced slopes in southern Spain, a process that evolves into gully formation. This analysis is supported by Lesschen et al. (2008), who found that over half of abandoned fields in southeast Spain show moderate to severe erosion, with calculated rates reaching up to 87 tonnes per hectare per year. These data clearly quantify how the loss of maintenance can translate into increased soil vulnerability to atmospheric agents.

In a broader review concerning Southern Europe, Stanchi et al. (2012) confirmed that the progressive abandonment of terraces leads to erosion and slope failures. They also highlighted that this process generates a generalised loss of soil consistency and mechanical properties, triggering various forms of instability, such as landslides and piping erosion.

More recently, Moreno et al. (2019) reiterated that piping erosion is the main instability phenomenon on terraced slopes in southern Spain, reaffirming a concept previously highlighted by Díaz et al. (2007).

The urgency of the problem is further underscored by the rapidity with which the structural decay of terraces manifests after abandonment. Stanchi et al. (2012) confirm, similarly to the findings of Cevasco et al. (2014), Brandolini et al. (2018), and Agnoletti et al. (2019) for the Cinque Terre area, that widespread collapse of dry-stone walls can be observed in relatively short periods, often after merely 12-15 years from the cessation of agricultural activities. This temporal evidence, emerging from various independent studies, highlights not only the intrinsic vulnerability of these structures in the absence of maintenance but also that this vulnerability is greatly enhanced, especially in the years immediately following abandonment.

In the national context, the phenomenon of terraced slope abandonment and its implications for stability have been the subject of several scientific studies. Among these, research conducted by Camera et al. (2014), Preti et al. (2018b) and Crosta et al. (2003) stands out for its focus on evaluating hydrological circulation within the terrace-dry-stone wall system and the interference of such dynamics with the stability of the wall structures.

In particular, the study by Camera et al. (2014), conducted on terraced slopes in Valtellina (Northern Italy), investigated the role of hydrological circulation within the terrace-wall system. To this end, the authors employed manual tensiometers and piezometers to monitor subsurface water conditions. The collected data were subsequently used to initialise a hydrological model, developed at the single-terrace scale using the SEEP/W module of GeoStudio. The results of this study highlight how the collapse of dry-stone walls and terraced slopes in the analysed area is predominantly correlated with the formation of perched water tables. Such water tables cause saturation of the infill material, compromising the stability of the structures. The authors also emphasise how this problem is significantly exacerbated by the presence of walls not subjected to regular maintenance (Figure 1.6).

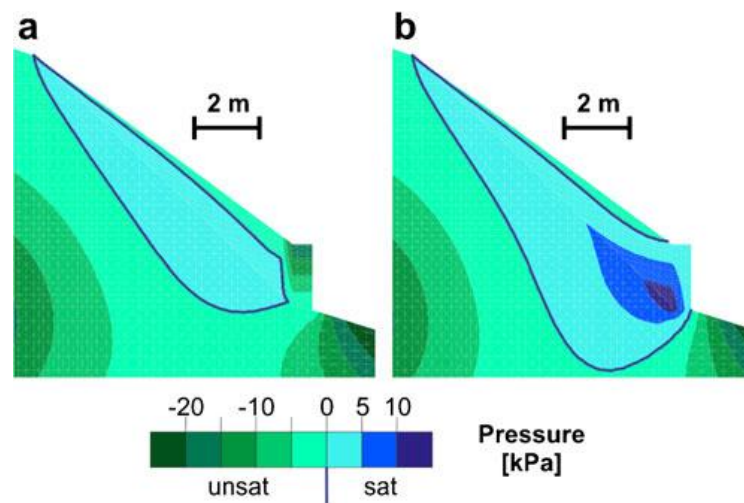


Figure 1.6 - The development of groundwater tables within the slope leads to increased pore water pressures. These pressures are lower behind a) well-maintained walls compared to those with a b) lack of maintenance (from Camera et al., 2014).

Conversely, the study by Preti et al. (2018b) acknowledges that wall collapse can originate from soil saturation due to the formation of a perched water table, even though it is not considered the only possible mechanism. Indeed, the authors propose a new model to understand water circulation within terraced systems. Specifically, their study considers the terraced slopes of Chianti (Tuscany, Central Italy). In the context analysed by the study, it was observed that water, whether from precipitation or irrigation, rapidly infiltrates the superficial soil layer, extending to approximately 0.5 m in depth. This layer, characterised by a high sand fraction and high hydraulic conductivity, facilitates the infiltration process.

The authors identified the presence of a highly heterogeneous and spatially discontinuous soil and subsoil structure within the terraces. This heterogeneity promotes the formation of

preferential flow paths and subsurface conduit systems (piping systems). Consequently, water does not percolate uniformly, saturating the entire terrace body, but rather propagates rapidly through these preferential channels as fast subsurface flow. Therefore, contrary to the hypothesis put forward by Camera et al. (2012) in the previous study, Preti et al. (2018b) assert that the water flow generated by subsurface conduit systems tends to accumulate behind the dry-stone walls. This accumulation is favoured by both the surface topography and the presence of discontinuities and preferential pathways in the subsoil immediately adjacent to the wall structures.

This localised accumulation leads to a significant increase in pore water pressure, which exerts critical stress on the wall, inducing a sequence of events that result in instability. The field evidence collected by the authors, which shows collapses confined to the wall elements themselves rather than the entire soil mass of the terrace, decisively supports the hypothesis of focused and localised hydraulic pressure against the wall elements, rather than generalised soil saturation (Figure 1.7).

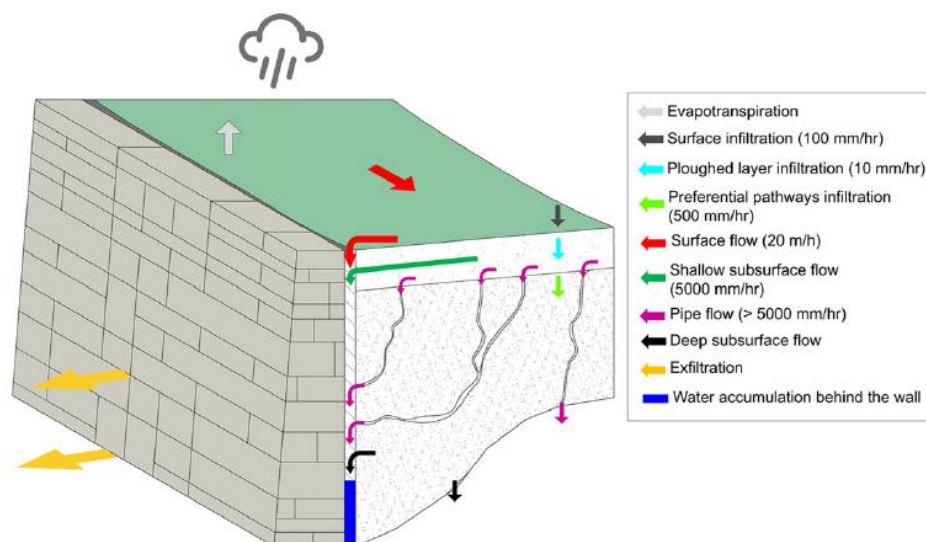


Figure 1.7 - Conceptual sketch of water circulation on a terraced slope and the process leading to water accumulation behind the wall, according to Preti et al. (2018a).

The various studies cited within this paragraph have consistently identified the instability of terraced slopes as an issue primarily correlated with land use dynamics and the abandonment of terraces. Indeed, these factors significantly influence hydrological circulation within the complex terrace-wall system, altering its equilibrium conditions.

Building on this consolidated scientific knowledge, other studies have progressively addressed their research towards the development of proactive risk management strategies. In this context,

monitoring emerges as a fundamental tool for: i) quantifying the issues underlying instability phenomena, thereby providing objective data; ii) implementing and validating hydrological and mechanical stability models; and iii) delineating and optimising mitigation strategies for these phenomena.

To this end, a recent study conducted in the Monterosso al Mare area, within the Cinque Terre National Park, by Fiorucci et al. (2023), had as its primary objective the understanding of hydrological dynamics in terraced soils, both in the short and long term, and their influence on slope stability. To achieve this, the authors implemented a hydrological monitoring system in the study area. This system involved the installation of sensors for measuring soil moisture and water potential, alongside a meteorological station for collecting climatic data.

The analysis of a two-year monitoring period allowed the authors to highlight several significant results. A clear correlation was observed between variations in soil water content and suction with seasonal events, indicating a cyclic dependence on annual climatic conditions. Furthermore, the authors emphasized that the soil texture, predominantly coarse-grained and of anthropogenic origin, facilitates rapid infiltration of rainwater into the soil profile, leading to abrupt and significant changes in volumetric water content. This behaviour implies an almost immediate hydrological response of the system to precipitation, which represents a critical factor for the stability of terraced slopes.

The collection and analysis of hydrological monitoring data play a crucial role in creating hydrological models representative of a specific site. These models are indispensable tools for assessing the stability of structures such as terraces, as highlighted by the studies of Preti et al. (2014, 2018b). In the cited studies, data from soil moisture and water potential monitoring instruments allowed for the calibration of a hydrological model describing water circulation in the investigated area. The authors stressed that this modelling was fundamental for defining water circulation dynamics and, subsequently, evaluating their influence on terrace stability through finite element analysis. In this manner, it was demonstrated that instability in these areas develops directly behind the retaining wall, primarily due to water accumulation.

A similar situation was addressed in the study by Camera et al. (2014), which focused on the terraced slopes of Valtellina. In this case too, data obtained from hydrological monitoring instruments were employed to construct a reliable hydrological model, which then enabled a stability analysis. The authors concluded that the instability of retaining walls in these areas occurs due to the formation of a superficial water table following prolonged rainfall events. According to their analysis, this instability originates from soil saturation, with the failure surface developing within the soil and propagating towards the wall (Figure 1.8).

These examples unequivocally demonstrate how an approach based on accurate monitoring data and robust hydrological modelling is essential for understanding instability mechanisms in terracing systems and for developing effective mitigation strategies.

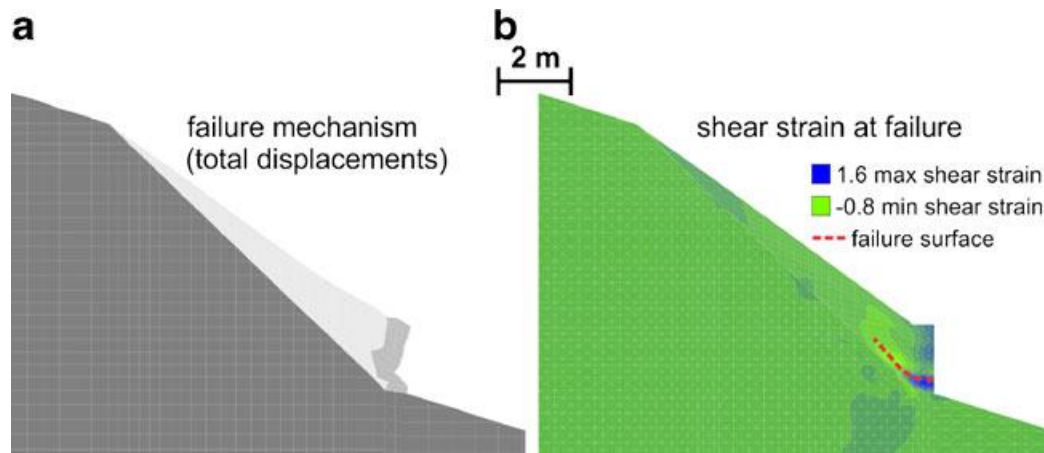


Figure 1.8 – a) Deformation and b) failure surfaces that develop behind the wall due to the accumulation of pore pressures (from Camera et al., 2015).

In conclusion of this review on the state of the art concerning the problem, it is clearly evident that the Cinque Terre area has experienced a growing incidence of slope instability phenomena in recent decades, as testified by scientific literature. These events, although predominantly localised along the step coastal slopes due to extremely high gradients, also frequently occur in inland areas. This issue is strictly correlated with the abandonment of agricultural terraces.

The instability of terraced slopes is recognised as a problem of global significance. The increase in such phenomena in recent decades has been significantly amplified by the greater frequency of extreme pluvial events, characterised by high intensity and short duration, attributable to the effects of climate change. Although such events are commonly identified as triggering factors, it is widely accepted in the literature that the process of terrace abandonment can act as a critical predisposing and/or preparatory factor. This process, which occurred in several phases during the past two centuries and is still ongoing, leads to severe alterations in hydrological circulation and surface runoff.

In more arid regions, the lack of surface water regulation following abandonment induces marked linear erosion processes. In the Italian context, such as the Cinque Terre's site, the process of terrace abandonment primarily influences the hydro-mechanical efficiency of dry-stone walls. Based on the previously cited studies, this can lead to a destabilisation of the wall, which can have a dual origin: the formation of a perched water table behind the wall, which saturates a portion of the soil, increasing pore pressures and causing collapse; or, alternatively,

collapse can result from a localised accumulation of water in the filling zone immediately behind the structure.

Therefore, it is evident that a lack of maintenance leads to a progressive modification of hydrological conditions within the terraced system which, in conjunction with extreme climatic phenomena, can culminate in the destabilisation of dry-stone wall structures. This firstly manifests through the appearance of localised bulges and ultimately with wall collapses.

Finally, the studies conducted highlight that land use management represents a crucial factor in the mitigation of instability phenomena. In this regard, there are studies in the literature that, although not specifically focused on terraced slopes, demonstrate the effectiveness of appropriate soil management practices in positively influencing the root development of vegetation. This development, in turn, imparts greater mechanical stability to the soil due to the reinforcement provided by the roots, significantly contributing to the mitigation of instability phenomena.

In this context, studies by Bordoni et al. (2014, 2021) underscore the critical role of correct management and maintenance of vineyard cultivations. Such practices directly influence root development, consequently impacting root reinforcement and density. Their research has also identified a correlation between root depth and the depth of potential failure surfaces.

This concept is further supported by numerous studies in the literature that focused on the contribution of root reinforcement to slope stabilisation in areas prone to shallow landslides. Recent works by Chok et al. (2015), Murgia et al. (2022), Masi et al. (2023), and Galeazzi et al. (2024) all highlight the role of plant root systems in stabilising slopes susceptible to shallow failures. These are just some of the studies addressing the topic of root reinforcement on slope stability. In this regard, in the work by Mao, Z. (2022), the author proposes a scientific review that summarizes and critically analyses the current state-of-the-art in the literature, offering a classification and perspective on the subject. Specifically, the paper analyses the similarities and differences between models belonging to two distinct approaches: the Wu and Waldron Model (WWM) and the Fibre Bundle Model (FBM). Based on this analysis, the author proposes new criteria for a more robust and representative classification of Root Reinforcement (RR) models.

Finally, a less explored approach, mainly due to the complexity of the variables involved, concerns the influence of apparent cohesion conferred to the soil through suction. This cohesion, defined as "hydrological", develops in the soil as a result of plant evapotranspiration

processes. Among the authors who have explicitly addressed this topic, the studies by Tarantino et al. (2023) are particularly relevant.

Similarly to what has been observed in previous studies, the stabilising effect of suction-induced cohesion is significant on slopes characterised by shallow landslides, where the failure surface develops just below the rooting depth. For the purpose of this work, the authors state that plant evapotranspiration represents a fundamental hydrological process that exerts a significant influence on the soil's water regime and, consequently, on its geotechnical stability.

This process involves the absorption of water from the soil by plant roots and its subsequent release into the atmosphere as vapour. This process leads to a progressive decrease in the water content within the soil profile. Such a reduction induces an increase in soil suction precisely in the vicinity of the root systems. The authors have highlighted that the increase in suction contributes to an increase in the effective stress in the soil, improving its mechanical properties and conferring a stabilising effect. The study also highlighted that the reduction in water content leads to a decrease in the unsaturated permeability of the superficial soil layers. Consequently, a reduced superficial permeability slows down the rapid infiltration of rainwater, which is particularly important during intense precipitation events. The authors note that this slowing of infiltration is crucial, as it promotes the maintenance of matric suction in the deeper soil horizons. In its absence, rapid saturation of the layers would nullify suction, thus reducing shear strength and significantly increasing the risk of instability and failures.

Other studies, such as the one by Chirico et al. (2013), evaluate the role of vegetation on slope stability in soils with a transient unsaturated regime, considering both the geo-mechanical effect and the hydrological effect of root reinforcement. The authors' objective is to provide indications on the relative weight of these two mechanisms. The study results show that the hydrological effect exhibits strong seasonal variability, while the mechanical effect displays limited temporal variability, and they did not find a close correlation between seasonal variation and root reinforcement.

It is fundamental to underline that the effectiveness of this process, understood as both hydrological and mechanical reinforcement, depends on vegetation maintenance. Well-maintained vegetation is essential to ensure the continuity of evapotranspiration processes and, consequently, the maintenance of apparent cohesion and soil stability.

1.2 RESEARCH OBJECTIVES

Existing literature has extensively documented the influence of varying land use on the development of landslide phenomena at the catchment scale. These investigations have been conducted both in the Cinque Terre area and in numerous national and international contexts (see, among others, Llorens et al., 1992; Harden et al., 1996; Díaz et al., 2007; Lesschen et al., 2008; Stanchi et al., 2012; Cevasco et al., 2013, Brandolini et al., 2018; Raso et al., 2018; Schilirò et al., 2018; Agnoletti et al., 2019; Moreno et al., 2019; Pepe et al., 2019; Di Napoli et al., 2020; Raimondi et al., 2023; Raso et al., 2020).

These contributions have focused on two main approaches: the implementation of landslide susceptibility maps for predictive analysis at the basin scale (e.g., by using both data-driven and physically based approaches) and the examination of the role of land use in instability phenomena that have already occurred. A unanimous finding from this literature review is that relatively short-term land abandonment can play a crucial role in influencing terraced slope instability.

Despite the extensive documentation at the catchment scale, there is a small number of slope-scale studies conducted specifically in terraced areas that aimed at quantifying the influence of land use on the overall slope stability. Most of the studies integrating the effect of vegetation (particularly root reinforcement) into stability analyses focused on natural slopes (Chok et al., 2015; Murgia et al., 2022; Masi et al., 2023; Galeazzi et al., 2024).

However, the results obtained in these contexts cannot be directly extended to terraced areas. The construction of terraces induces substantial modifications to the slope morphology and significant alterations to hydrological circulation. These structural and hydraulic variations represent key factors that make the geomechanical behaviour and hydrogeological response of terraced slopes intrinsically different from natural ones, requiring a specific study approach.

The situation is different for studies undertaken at the single slope scale to detail the influence of terrace abandonment and its consequences in terms of hydrological circulation on the stability of the individual terrace-dry-stone wall system (Camera et al., 2014; Preti et al., 2018b). Indeed, some studies in the literature have investigated the hydrological consequences of terrace abandonment, evaluating the pore pressures that develop behind the wall when the efficiency of its drainage system is modified by abandoned conditions.

The current state-of-the-art concerning terraced slopes reveals a significant gap in studies that comprehensively integrate hydrological, geotechnical, and climatic monitoring for the quantitative analysis of factors influencing the stability of terraced systems at both the hillslope

scale and the individual dry-stone-wall terrace system scale. In particular, there is a noted deficiency in investigating the hydrological dynamics developing on slopes in response to variable water regimes, as well as in quantifying the contribution of vegetation to stability analysis.

Based on this evidence, the present study aims to expand knowledge in this field, with a specific focus on the Manarola area (Cinque Terre). As highlighted in the literature (Brandolini et al., 2018), instability in these areas manifests either as a phenomenon affecting the entire hillslope or as a localised failure of the individual dry-stone-wall terrace system. Therefore, the main objective of this work is to investigate the quantitative influence of factors conditioning stability in these areas, adopting a multiscale approach (hillslope scale and local scale).

Specifically, within the field of local-scale analysis, the primary objective is to quantify water circulation through hydrological monitoring systems. This quantification is essential for constructing reliable hydrological models that account for the influence of different land-use conditions across various hydrological phases.

Subsequently, the focus shifts to the identification and evaluation of factors influencing the stability of these areas. This is achieved through numerical modeling, which includes flow analysis and fully coupled hydro-mechanical analyses. Particular emphasis is placed on the differential role of vegetation cover.

The coupled models enable the definition of interactions between the soil and its structure, quantifying this relationship by means of total horizontal stress values, as a function of the different hydrological and land-use conditions.

The development of these models is based on the analysis of data acquired via hydrological and mechanical monitoring systems installed at selected sites, representative of the different local land-use conditions: cultivated, long-term abandonment, and short-term abandonment.

In this study, the contribution of vegetation is modeled exclusively as additional soil cohesion (matric suction) induced by the evapotranspiration processes typical of unsaturated soils. This cohesion, which derives from water suction, increases the soil shear strength. The effect of mechanical root reinforcement was deliberately excluded from this work because the primary objective of the research is to evaluate the factors influencing the stability of terraced slopes in relation to hydrological dynamics. Conversely, mechanical root reinforcement is generally considered quantitatively constant in the short term, as it does not vary as a function of hydrological phases. Instead, it solely depends on the plant type, its vital state, and the slope geometry, as extensively documented in the literature (Prete 2006; Hales et al., 2009; Epis, 2010; Bordoni et al., 2014, 2021). The analysis conducted under unsaturated soil conditions

assigns a predominant weight to evapotranspirative processes compared to the mechanical contribution of the roots. This methodological choice proves to be not only more representative of short-term dynamics but also more conservative. As highlighted by Chirico et al. (2013), while the mechanical root reinforcement remains almost constant between the wetting and drying periods, the cohesive contribution due to evapotranspiration is reduced during wetting phases. Adopting this lower value therefore ensures a stability assessment in a conservative scenario.

The totality of these analyses allows, firstly, for a detailed assessment of the hydrological circulation and, secondly, for the definition and quantification of the factors influencing the stability of the terraced slopes as a function of the different hydrological phases, with a particular focus on the role of vegetation.

1.2.1 Principal aims and activities of the “Stone Wall for Life Project”

The 'Stone Wall for Life' project is an initiative of fundamental importance, co-financed by the European Union's LIFE Programme, dedicated to the recovery and restoration of terraced systems characterised by dry-stone walls and associated hydraulic regulation works. The scientific rationale of the project lies in the necessity to increase the resilience and resistance of fragile territorial contexts that are at high hydrogeological risk, with a primary focus on the Cinque Terre National Park area in Italy. The main objective is to recover and maintain the structural integrity of these historical artefacts, which are essential for slope stability and for counteracting the detrimental effects of extreme weather events, which are increasingly intense due to climate change. Therefore, a crucial action of the project is the reconstruction of extensive sections of dry-stone walls that are in an advanced state of degradation and abandonment.

Beyond the immediate structural intervention, the project pursues long-term monitoring objectives aimed at quantifying the beneficial effects of the restored walls on the territory's capacity to adapt to climate change. This empirical data forms the basis for the subsequent development of climate adaptation plans, specifically intended for local administrations, with the aim of providing preventative and mitigation strategies that are replicable. To this end, the project includes studies aimed at assessing the potential replicability of the methodological approach in other sites that share analogous geomorphological conditions, both within the Park area itself and in different European territorial contexts.

To achieve these objectives, in-depth field observations and site-specific analyses were conducted within the scope of this project to identify study areas that were fully representative of the diverse conditions of land use and degradation. Once the sites were selected, the methodology involved a detailed physical-volumetric and geotechnical characterisation of the subsoil and the wall structures. Subsequently, the most suitable instruments for the hydrological, mechanical, and climatic monitoring of the sample sites were chosen and installed. The installation and management of this complex instrumental network were carried out in close institutional collaboration with the Applied Geology group of the Department of Earth, Environment and Resources at the University of Naples Federico II, ensuring a high degree of scientific rigour in data acquisition.

The present PhD research has been strategically positioned within this operational and scientific framework, leveraging the wealth of characterisation and monitoring data collected within the LIFE project. The central objective of the thesis is the development of reliable numerical models that utilise this empirical data for calibration and validation. These models aim to simulate the hydro-mechanical behaviour of the terraced systems, thereby providing essential quantitative and predictive results. The final contribution of the PhD research is twofold: on the one hand, to strengthen the scientific understanding of the stability mechanisms of dry-stone walls; on the other hand, to provide mitigation and prevention tools directly usable by local administrations to effectively combat hydrogeological risk in terraced contexts.

1.3 STRUCTURE OF THE THESIS

This thesis is divided into seven chapters, each one addressing a specific aspect of the conducted investigation.

Chapter 1 outlines the research context, presenting the state of the art and defining the specific objectives of the work.

Chapter 2 provides a detailed description of the study area, exploring its geographical, geological, geomorphological, and hydrographic characteristics. Particular attention is dedicated to terraced systems. After a general overview of the context, the chapter focuses on analysing case studies, identifying and describing their specific features. For each site, the morphological and geological characteristics are defined, along with the structure of the dry-stone walls. This in-depth investigation allows for a comprehensive description of the dry-stone-wall terrace complex, evaluating parameters such as terrace slope, soil stratigraphy, wall type and state of preservation, in addition to the different types of vegetation cover.

Chapter 3 describes the investigation methodologies in detail, organised into paragraphs for clarity. The chapter begins by illustrating the adopted monitoring system, describing the sensors and their installation procedures. The chapter proceeds with a description of the methodology adopted for a slope-scale investigation, with a particular focus on the preliminary slope stability analysis. This analysis was performed using the Finite Element Method (FEM), and specifically, the Shear Strength Reduction (SSR) analysis. Based on the information obtained from the preliminary stability analysis, the study focused on a detailed, local-scale analysis of the individual terraced systems that characterize the three investigation sites. The main objective is to develop a reliable hydrological model using monitoring data and then validate it through a transient flow analysis in the GeoStudio software. Before illustrating the adopted methodology, a theoretical section was presented describing the hydrological and mechanical behaviour of unsaturated soils, with particular attention to Rankine's theory of earth pressure and the role of evapotranspiration. Based on the hydrological model's validation, the limit equilibrium slope stability methodology was applied, using the GeoStudio Slope/W module, to evaluate the impact of pore pressure variations at the three investigation sites on limiting the stability of the slope. The chapter proceeds with a detailed description of the methodology adopted for the development of a coupled hydro-mechanical analysis in PLAXIS. This approach is crucial for simultaneously investigating the cause-and-effect relationship between hydrological variations that induce ground deformation and the subsequent generation of horizontal stresses at the soil-structure interface.

The results of the previously conducted analyses are described separately in Chapters 4, 5, and 6 to offer a clearer and more organised overview. Specifically, Chapter 4 presents the results of the site characterisation tests, the interpretation of which allowed for the development and construction of the engineering-geological model.

This model was fundamental as a basis for setting up the finite element stability analysis at a slope scale, the results of which are presented in Chapter 5. In Chapter 5, the results of the slope stability analysis for the different site conditions are presented. Based on these results, the procedure that allowed the transition from a global-scale analysis to a detailed analysis is illustrated.

A quality assessment of the acquired monitoring data was conducted before proceeding with the hydrological modelling. The data quality assessment allowed for the development of a reliable hydrological model, which was calibrated using valid experimental data. This model was then used for the hydrological simulations performed with the GeoStudio software. The modelling validated the calibrated hydrological model and defined a precise dynamic of

hydrological circulation on the slopes, focusing in particular on the development of pore water pressures and their influence on the slope's limit equilibrium. Based on these results, factors such as site characteristics and land use conditions that influence the development of more critical relative stability conditions were investigated.

Chapter 6 details the results of a coupled flow and deformation analysis performed using the PLAXIS software. The primary objective was to develop a robust hydromechanical model by integrating the previously validated hydrological model with the mechanical response of the soil. This model was essential for investigating how changes in water flow (i.e., the flow regime) directly influence soil movements and pressures (i.e., the deformation response). To ensure the model's reliability, the numerical modelling results, expressed as total horizontal stresses, were compared against the total pressure data recorded in situ (via pressure cells at site 850). This comparison was fundamental for studying the interactions between the flow regime and the system's deformation response, and for evaluating the lateral pressures exerted on the back of the wall structure. Finally, the mathematical model was employed to isolate and quantify the influence of a single factor: namely evapotranspiration (ET), which is closely linked to the type of vegetation present. By leveraging the specific hydrological and geometrical conditions of site 850, the analysis allowed for an assessment of the extent to which different types of vegetative cover modify surface water regimes and, consequently, alter the lateral pressures acting on the wall structure. Essentially, the study quantified how vegetation can act as a control element for earth pressures on the wall.

Finally, the concluding chapters present critical discussions of the results obtained and the conclusions of the research, critically analysing the role of this work within the broader scientific community and outlining possible future prospects.

Following the concluding chapter, two appendices are included for documentary purposes. These consecutively present the standardized methodological protocols employed for the geotechnical characterization campaign (in-situ and laboratory tests) and the resulting raw and processed data. This data constitutes the fundamental information corpus for the development of the geotechnical model and subsequent numerical analyses. The decision to relegate these methodologies to an appendix is motivated by the fact that they are established, publicly available investigation procedures.

CHAPTER 2 – STUDY AREA

2.1 GEOGRAPHICAL SETTING

The toponym "Cinque Terre" denotes a 20 km stretch of rocky coastline in eastern Liguria, NW Italy, situated between the Mesco and Monesteroli headlands within the Province of La Spezia. This toponym is historically derived from its five constituent villages: Monterosso al Mare, Vernazza, Corniglia, Manarola, and Riomaggiore (Terranova, 1989).

The present study focuses on the area known as the "amphitheater" of Manarola, a village (Figure 2.1) representing one of the jewels of the Cinque Terre. This segment of the eastern Ligurian coast is universally recognized for its exceptional landscape and cultural value. Manarola's geographical location is intrinsically linked to its identity and distinctive morphological characteristics. The village is situated approximately 70 km southeast of Genoa and 8 km northwest of La Spezia, nestled between the villages of Corniglia to the northwest and Riomaggiore to the southeast. Its inhabited core develops on a rocky promontory that boldly extends into the Ligurian Sea, part of the Mediterranean Sea basin. The prevailing climate in the area is typically Mediterranean.

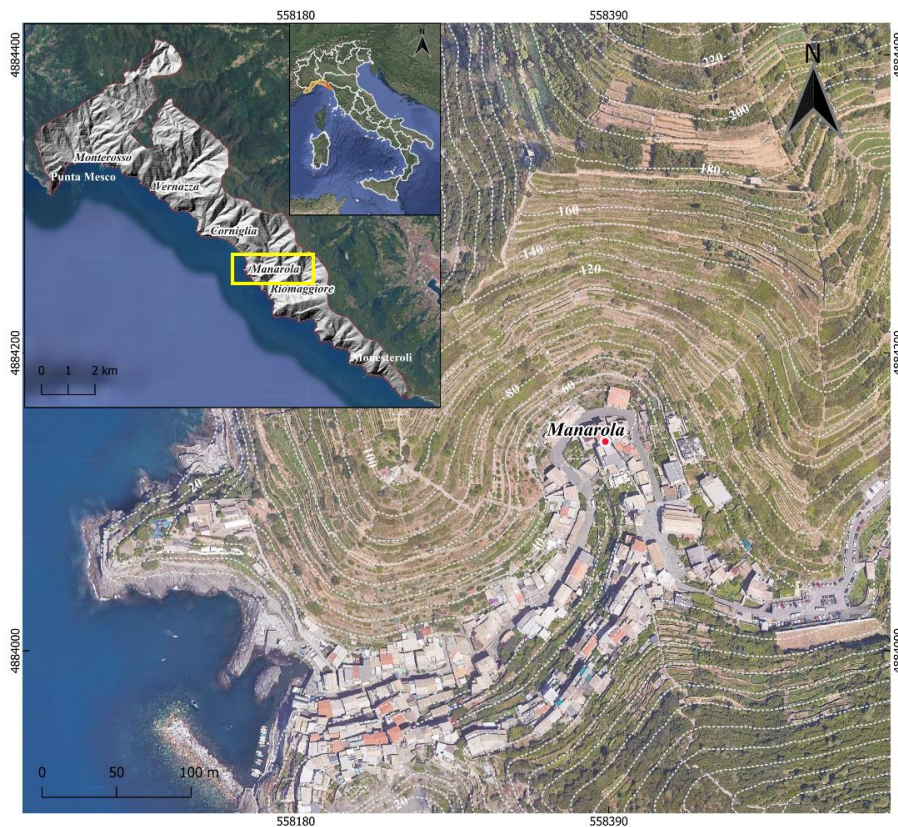


Figure 2.1 - Geographical setting of the Manarola study area within the Cinque Terre National Park.

This site embodies a typical landscape unit of the vineyard areas within the Cinque Terre National Park. Since 1997, the Cinque Terre have been included in the UNESCO World Heritage List as a Cultural Landscape, while in 1999 it was declared National Park.

According to UNESCO's guidelines, this category encompasses "landscapes that represent the combined work of nature and of humankind, and that illustrate the evolution of a society and its settlement over time, under the influence of the physical constraints and/or opportunities presented by its natural environment and of successive social, economic and cultural forces."

The amphitheatre's morphological setting is the result of a synergy between natural geomorphological dynamics and human activity which, over past centuries, shaped the territory by creating terraces. These narrow and almost flat surfaces sustained by dry-stone walls were made cultivable, particularly for viticulture. This anthropogenic system plays a crucial hydro-geomorphological role as well. Indeed, agricultural terraces contribute to mitigating the slope's steepness, facilitating adequate rainwater drainage and significantly reducing the risk of surface runoff and soil erosion (Bernini et al., 2021).

Despite its proximity to the sea, the Cinque Terre exhibits an orography typical of hilly-mountainous environments. The slopes are exceptionally steep, valleys are deeply incised, and the small hydrological basins are fed by ephemeral watercourses (Cevasco et al., 2015).

From a climatic perspective, these areas experience hot, dry summers and mild winters. The average annual temperature ranges between 14.5 and 15.5 °C, peaking at an average of 22–24.5 °C in July and August, and reaching a minimum of 7–8 °C in January. The average annual rainfall is 1040 mm, with the highest precipitation levels typically occurring from October to December (Brandolini et al., 2017).

Owing to these unique geological, geomorphological, and climatic conditions, the Cinque Terre region has been traditionally shaped by distinctive land-use practices. Over the centuries, large extent of the natural slopes has been terraced for the cultivation of olive groves, orchards and, pre-eminently, vineyards. This ingenious system has created a unique coastal landscape and terroir, internationally recognized for the production of esteemed wines such as "*Vermentino*" and "*Sciacchetrà*" (Brandolini et al., 2017). However, these cultivation practices have undergone a significant decline since the end of the nineteenth century and mostly during the last century, primarily due to rural exodus. The progressive abandonment of terraced areas has favoured a substantial increase in soil erosion and slope degradation. Currently, it is estimated that only about 33% of the terraces remain cultivated (Raso et al., 2021). The preservation and restoration of these terraces represent a crucial challenge for landscape conservation, prevention

of slope degradation, and the sustainability of traditional agricultural activities in the Cinque Terre.

2.2 GEOLOGICAL SETTING

The Cinque Terre National Park, covering an area of 38 km², is located in the easternmost part of the Liguria region, in northwest Italy. Geologically, this area constitutes a NW–SE oriented segment of the Northern Apennine orogenic chain. This chain formed over an extended period, from the Late Cretaceous to the present day, as a result of the convergence between the European Plate and the northern promontory (Adria) of the African Plate. During the subduction phases, an accretionary prism developed (Terranova et al., 2006; Brandolini, 2017) (Figure 2.2).

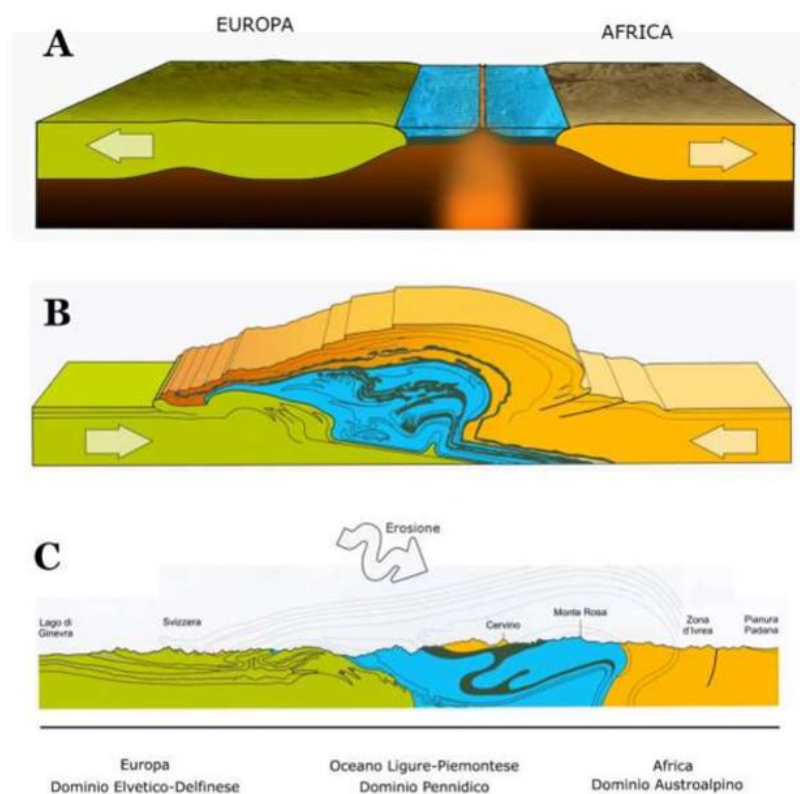


Figure 2.2 - Geological evolution of the Northern Apennine chain (from Bosellini, 2005).

This accretionary prism is characterised by deposits from the Ligurian-Piedmontese oceanic basin that were involved in the subduction process, forming the tectonic nappes. These nappes are representative of the following palaeogeographical environments that characterised the Ligurian-Piedmontese Ocean basin (Bosellini, 2005) (Figure 2.3):

Internal Ligurian Domain: it represents the deepest and most internal portions of the oceanic accretionary prism. These were the first units to be deformed and overthrust during subduction.

External Ligurian Domain: it corresponds to oceanic or transitional successions, deposited in more external positions within the Ligurian-Piedmontese basin, which overlies the preceding units of the Internal Ligurian Domain.

Sub-Ligurian Domain: these units represent transitional successions, which are overthrust by the Ligurian units and are often considered as deposits from basins more proximal to the Adria continental margin.

Tuscan Domain: this domain represents the sedimentary succession of the Adria continental margin (i.e., the Tuscan Platform). The Tuscan Nappe, characterised by carbonate and turbiditic formations, is detached from its basement and overthrust eastwards by the Ligurian and Sub-Ligurian units.

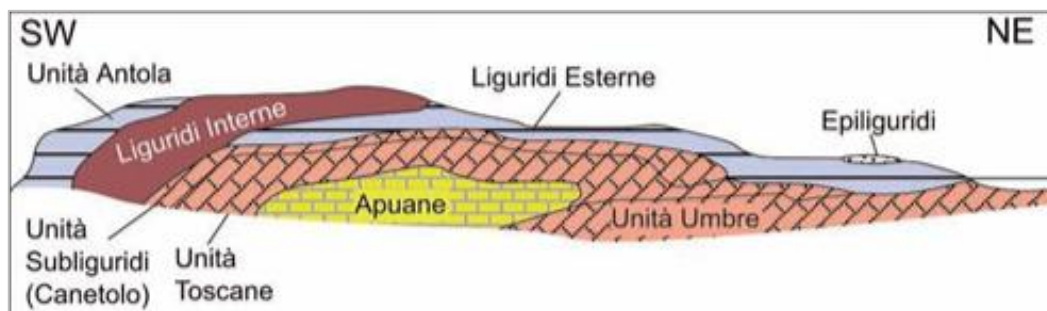


Figure 2.3 - Conceptual sketch of the Ligurian-Emilian Apennine geological evolution (from Elter P., 1994).

The geological structure of this area is complex and highly tectonised, primarily due to subduction processes that have induced significant both brittle and ductile deformations. Examples of these tectonic structures encompassing the entire Cinque Terre area include the tectonic contact between the Canetolo Shale and Limestone Formation and the Macigno Formation, as well as a large south-westward verging antiform fold, developed during the Tertiary orogenic phases.

The principal tectonic units outcropping in the Cinque Terre National Park are listed below, following a top-to-bottom sequence, i.e., from the oldest units to the most recent deposits (Figure 2.4).

Internal Ligurian Domain

- Gottero Unit: it outcrops in the westernmost sector of the National Park, consisting of a turbiditic sequence (Late Cretaceous – Early Palaeocene), which includes quartz-feldspathic and micaceous sandstones with thin argillaceous interbeds, and occasionally polygenic conglomerates.
- Bracco-Val Graveglia Unit (or Bracco Unit): it outcrops in the westernmost sector, primarily consisting of ophiolitic rocks (Middle Jurassic), such as cherts, gabbros, and serpentinites.

External Ligurian Domain

- Ottone Unit: it is located in the western part of Monterosso al Mare and in the central sector of the National Park, predominantly composed of pelitic rocks.
- Monte Veri Unit: it is characterised by grey-black laminated clays with lenses and blocks of “*Palombini limestones*” and fine sandstones, and the presence of lenses of polygenic ophiolitic breccias and granitic breccias.

Sub-Ligurian Domain

- Canetolo Unit: it outcrops in the central part of the Cinque Terre, particularly in the Vernazza basin and along the coast between Corniglia and Manarola. It is composed of clays with intercalations of limestones and silty-arenaceous turbidites (Palaeocene – Early-Middle Eocene) and fine arenaceous turbidites (Late Oligocene).
- Marra Unit: it outcrops in the western part of Monterosso al Mare and in the central sector of the National Park showing shales with limestones and silty-sandy turbiditic rocks.

Tuscan Domain

- Tuscan Nappe (Macigno): it occupies most of the Cinque Terre territory and it is primarily made up of thick arenaceous-argillaceous turbidites, known as the Macigno Formation (Late Oligocene). It widely outcrops along the coast and especially in the Manarola area.

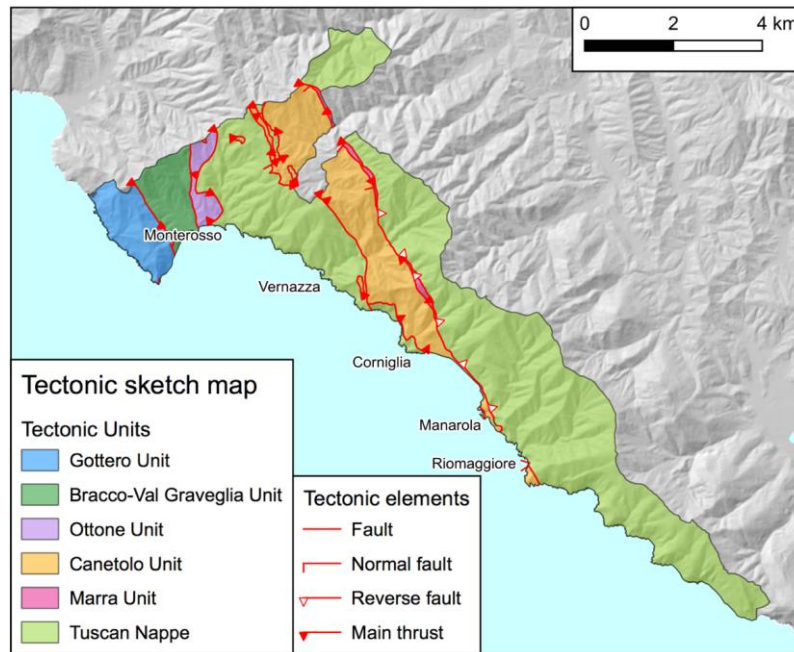


Figure 2.4 - Tectonic sketch map of the Cinque Terre National Park, showing the six Tectonic Units (from Bernini et al., 2021).

Specifically, the Manarola study area is characterised by the presence of the Tuscan Nappe unit and of the Canetolo unit.

In this area, the Tuscan Nappe consists of an arenaceous-silty turbiditic flysch, made up of medium- to coarse-grained sandstone beds with thin siltstone interlayers, and of a fine-grained arenaceous turbiditic flysch with siltstones (the "Macigno Fm., MAC" *strictu sensu* and the "Riomaggiore Banded Sandstone Lithofacies, MACa"). The Canetolo Unit, conversely, is represented by fine-grained arenaceous turbidites (the "Ponte Bratica Sandstone Fm., ARB") and shales with limestones and arenaceous-silty turbidites (the "Canetolo Shale and Limestone Formation, ACC") (Bernini et al., 2021).

From a geo-structural perspective, the area is characterised by the tectonic contact between the Canetolo Shale and Limestone Fm. and the Macigno Fm. This contact is interpreted as a high-angle reverse fault (Abbate, 1969) (Figure 2.5).

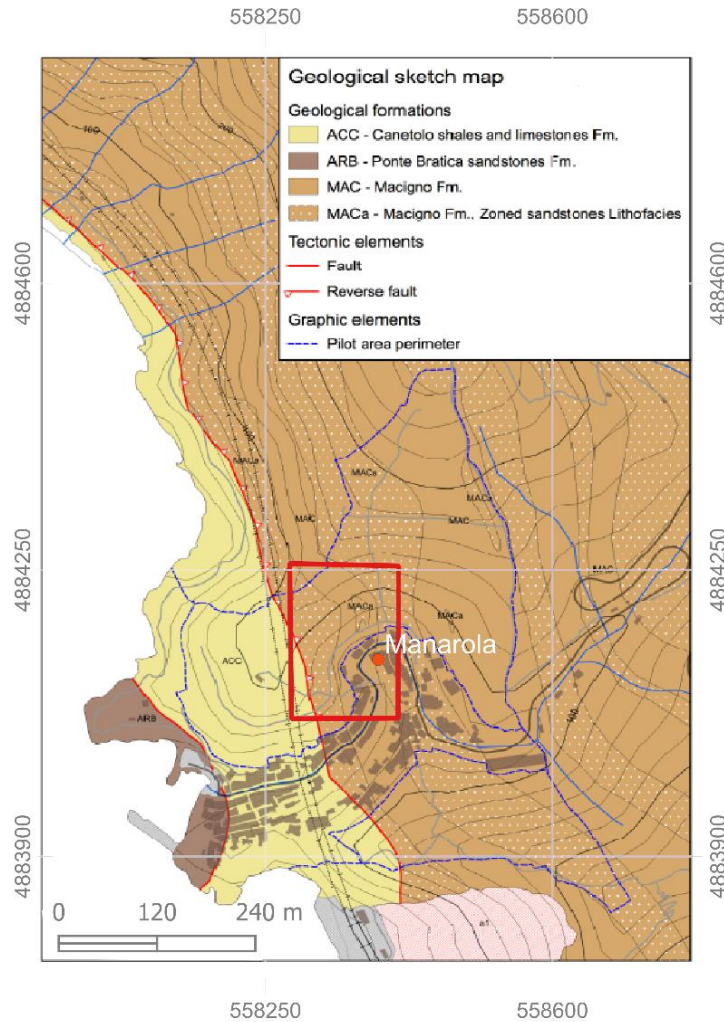


Figure 2.5 - Geological map of the study area (from Bernini et al., 2021).

2.3 GEOMORPHOLOGICAL SETTING

From a geomorphological perspective, both the orientation of the coastline and the drainage network are largely influenced by tectonic lineaments (i.e., fault and fracture systems), primarily with NW–SE and NE–SW orientations, and secondarily N–S and E–W.

The watercourses are short, steep, exhibiting ephemeral hydrological regimes, marked by a high erosive capacity and by significant sediment transport potential, resulting in the formation of short and deeply incised valleys.

Consequently, due to the high steepness of its slopes, with over 50% of the terrain characterised by gradients ranging from 30° to 40°, and its hydrological regime, the geomorphological landscape of the Cinque Terre is dominated by gravitational processes and surface runoff, both linear and areal. Along the coast, the gravitational processes interact with marine erosion,

leading to the presence of several large coastal landslides with heights ranging from 5 to 100 m (Figure 2.6).



Figure 2.6 – Examples of gravitational processes along the Manarola coast (from Brandolini et al., 2017).

Because of the intense rainfall that regularly affects the area and the high steepness of the slopes, which are typically covered by thin (on average 1-2 m thick) eluvial-colluvial deposits, shallow landslides and debris flows are widespread throughout the Cinque Terre. Shallow landslides are primarily represented by earth and debris slides that often evolve into flows, with a failure surface often coinciding with the contact between the detrital cover and the bedrock. Such landslides particularly affect terraced slopes (Cevasco et al., 2007; Pepe et al., 2019; Raso et al., 2019).

These geomorphological characteristics are extensively widespread across the entire Cinque Terre, and particularly within the municipality of Manarola. The area of Manarola is characterised by extensive slope portions and slope debris that have been profoundly modified by human actions through the construction of terraces (Figure 2.7).

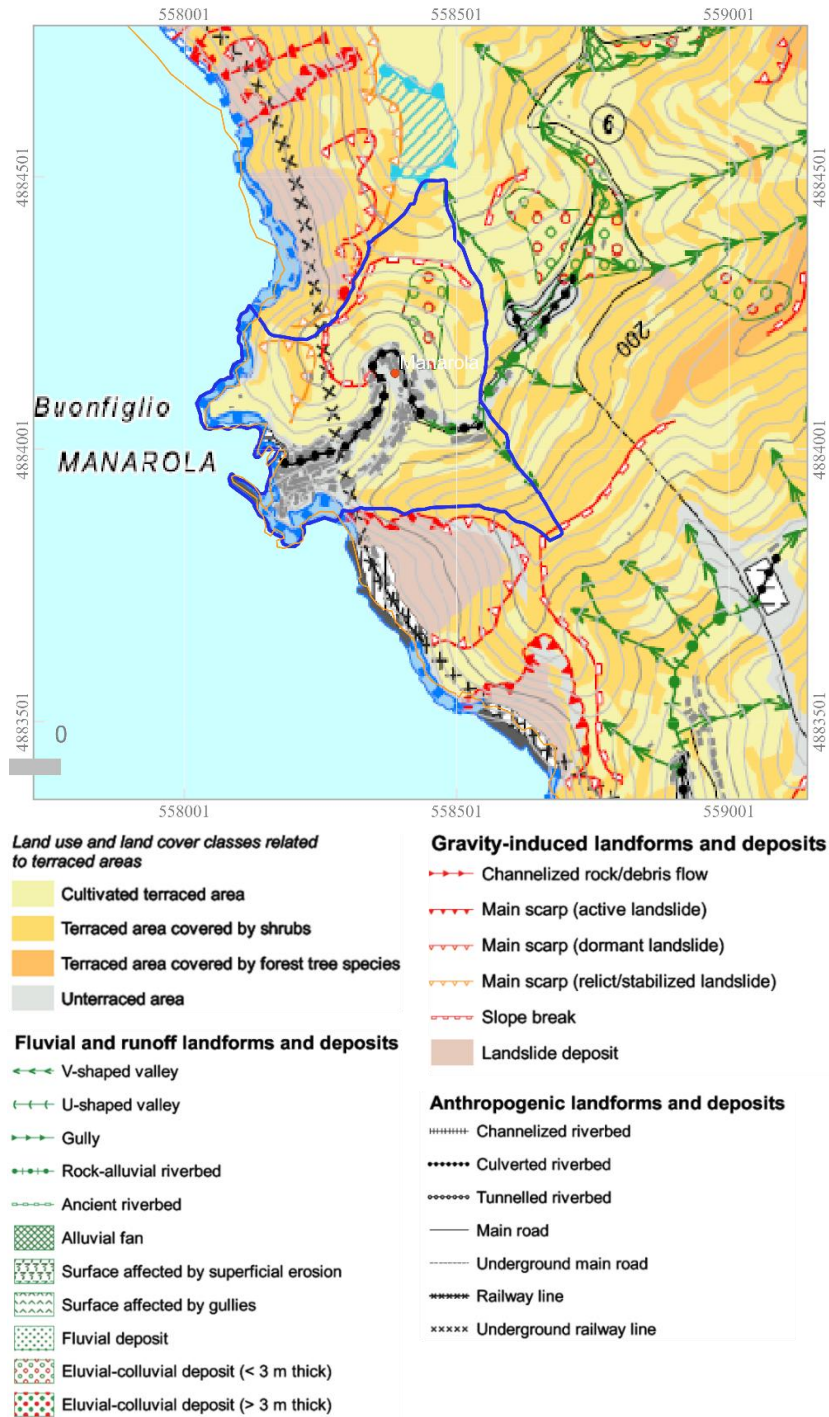


Figure 2.7 - Geomorphological map of the study area (from Raso et al., 2021). The study area of Manarola is indicated in blue.

Specifically, the settlement is surrounded by an amphitheatre-shaped slope, entirely terraced, primarily dedicated to the cultivation of olive groves and vineyards, from which the “*Sciacchetrà*” Cinque Terre DOC wine is produced (Figure 2.8).



Figure 2.8 – View of the morphology of the Manarola terraced amphitheatre.

However, a significant portion of these terraces has undergone agricultural abandonment, with a consequent growth of the vegetation cover towards shrubs and forest formations.

The study area is predominantly characterised by anthropogenic landforms. In particular, terraces represent 60-65% of the territory, with bench widths varying from 2 to 4 m and heights ranging between 1.5 and 2.5 m. These terraces have modified the slope geometry and, consequently, the minor drainage network that drains the hillside. The presence of terracing leads to the creation of other anthropogenic landforms such as dry-stone walls, underground cisterns, artificial drainage channels, and pathways (Figure 2.9).

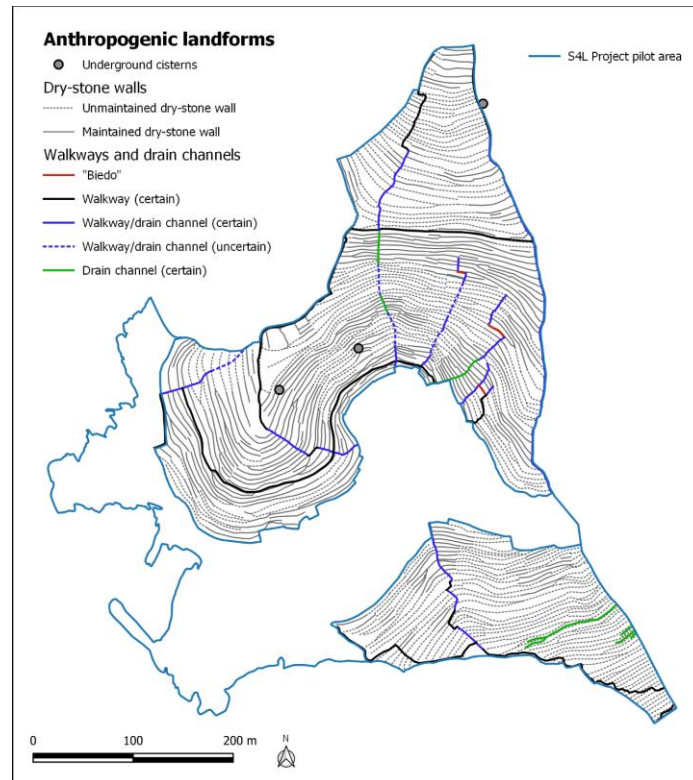


Figure 2.9 - Map of anthropogenic structures in the Manarola area (from Bernini et al., 2021).

Within the study area, slope instability processes are associated with the partial or total collapse of retaining walls (Figure 2.10). Generally, following the initial failure, the evolution of the instability can lead to further wall collapses, aligned along the maximum slope gradient, both downslope and upslope.



Figure 2.10 - Examples of wall collapses in the study area, developing along the line of maximum slope (from Bernini et al., 2021).

Regarding fluvial processes, the drainage network in the area under examination is entirely artificial, with no identifiable natural channels. Occasionally, small artificial channels (approximately 10-20 cm wide) are found at the base of the walls, conveying water laterally

and then downslope (Figure 2.11). Generally, the main drainage network comprises small artificial channels, shaped both parallel and perpendicular to the walls on the slope, with a variable width between 0.5 and 1 m, and very often coinciding with the pathways. Furthermore, the sub-horizontal terraced surfaces exhibit a notable decrease in elevation towards their frontal and lateral edges (Figure 2.11). This gradient has been designed with the objective of promoting surface runoff.



Figure 2.11 - On the left, a drainage channel at the base of a wall is illustrated; on the right, the sub-horizontal inclination of a terrace is visible (from Bernini et al., 2021).

Terraces sparsely covered by vegetation and cultivated areas lacking grass are affected by splash erosion and sheet erosion. In some cases, erosive forms resembling rills and gullies affect the terrace surface located upslope of a collapsed wall (Bernini et al., 2021).

2.4 AGRICULTURAL TERRACE CHARACTERISTICS

Terracing is an agricultural practice of ancient origin, with examples dating back to the Roman era, primarily used as gardens for Roman villas. During the Early Middle Ages and the barbarian invasions, the practice of terracing was once again encouraged for the development of agriculture. Historical sources indicate that the Ligurian terraced landscape reached its maximum expansion between the 18th and 19th centuries, due to demographic increase and the repopulation of rural areas. This led to the widespread cultivation of specialised crops such as vines, olives, and subsequently lemon groves (Brancucci et al., 2000).

The soil on terraced lands is not naturally present; instead, it is created through arduous transformations of the original landscape. This process involves a profound re-elaboration of the natural slope profile.

The process begins with the preparation of the laying surface, which is cleared of protruding stones. Subsequently, a dig is excavated into the weathered rock basement to create a counter-slope base, namely the so-called "*scarpa*" in Italian (important for the wall's stability). After this procedure, the first row of stones, which forms the foundation of the wall structure, is positioned. Subsequent stones are arranged in superimposed horizontal layers named as "*corsi*" in Italian (Brancucci et al., 2000) (Figure 2.12). The construction process ends with the creation of horizontal or slightly inclined surfaces, which permit cultivation.

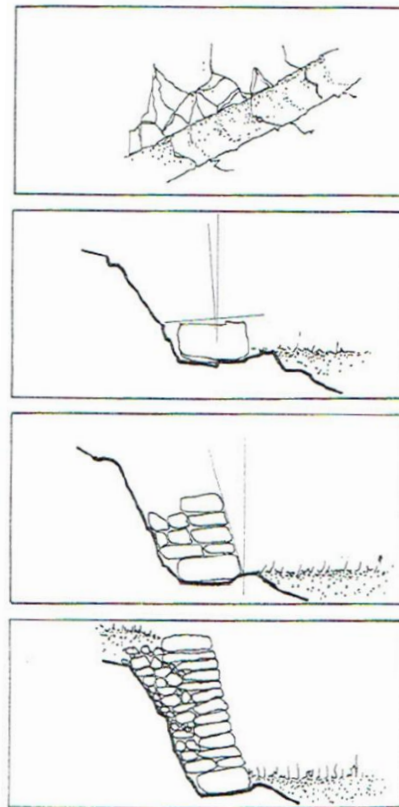


Figure 2.12 - Main stages of slope terracing (from Brancucci et al., 2000).

The small voids created between rock elements are filled with smaller stones to allow for effective water drainage and to prevent the passage of fine soil. Subsequently, between the wall and the excavated material, debris, gravel and small pebbles are placed to form a protective drainage layer for the wall. Once the established level is reached, this drainage layer is covered with compacted soil (Figure 2.13).

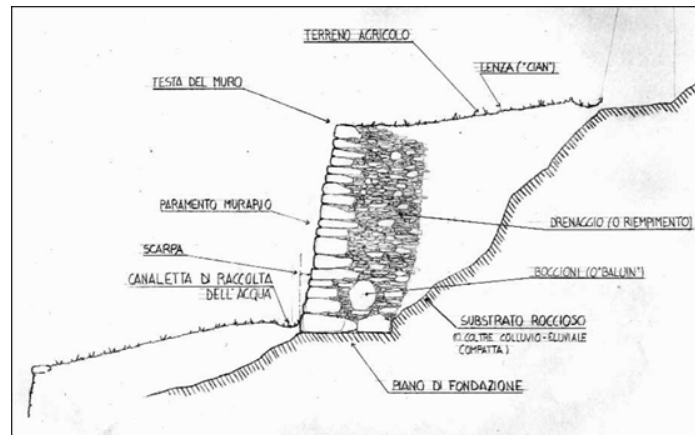


Figure 2.13 – Key elements constituting a dry-stone wall terraced system (from Brancucci et al., 2000).

In particular, the foundation is highly important as it represents a key element in conferring stability to the retaining masonry. The characteristic of the foundation depends on the nature of the substratum:

- **Rock substratum:** soil and highly weathered rocks that might hamper effective anchoring are removed. If the basement has a negative inclination (i.e., tending to cause the wall base to slide downslope), to counteract the soil pressure, either a step is created to place the foundation elements on a horizontal plane or a slightly inclined upslope base.
- **Weak substratum (e.g., soil layer):** the foundation base must be horizontal or slightly inclined upslope (approximately 10% gradient). If the soil is compact, excavation can be to 20-30 cm deep; otherwise, it is necessary to deepen the excavation until a more compact layer is reached (Besio, 2004). The geometry of the base depends on the wall's height; thus, up to 1.50 m high walls typically have a foundation with a width of 50 cm, while for wall heights between 2 and 3 m, the foundation is approximately 70 cm (Besio, 2004).

The construction procedures explained above are designed to enable the wall to resist the pressures from the original soil material and the reworked drainage material behind the wall, as well as those from water infiltration during/after rainfall events. The drainage function operated by both the dry-stone wall and the backfill is fundamental for counteracting and dissipating the pore pressures that arise during intense pluviometric events.

Therefore, when terraces are no longer maintained, especially for prolonged periods, a progressive alteration of the soil's mechanical characteristics occurs, and, in particular, a modification of the drainage function efficiency. This phenomenon negatively impacts the

retaining wall's capacity to resist the increased horizontal pressures exerted by the soil. In most cases, these conditions degenerate into a localised collapse of the structure.

In the study area, the dry-stone walls were generally founded on a geological substratum attributable to the Macigno Fm. In the literature, this formation has been identified as particularly suitable for agricultural activities, with a specific suitability for vineyards (Terranova et al., 2006). Within the study area, based on data from previous studies (Raso et al., 2021), it has been possible to subdivide the terraced surfaces into three main classes (Figure 2.14).



Figure 2.14 – Examples of different land-use conditions identified along the terraced slopes: 1) cultivated vineyard (green); 2) terrace in an early stage of abandonment (orange); 3) terrace abandoned for decades (red).

Cultivated Terraced Area

This category includes terraces currently cultivated, characterised by vineyards, olive groves, and citrus groves. Approximately 50% of the terraced areas in Manarola fall into this category (Figure 2.15).

Terraced Area Covered by Shrubs

These areas can be considered recently abandoned (about 20 years). They approximately consist of 37% of the terraced areas and are covered by shrub vegetation.

Terraced Area Covered by Forest Tree Species

These terraced lands are considered to have been abandoned for decades, featuring dense forest cover. Approximately 13% of the terraced areas in Manarola fall into this category (Figure 2.15).



Figure 2.15 - Characteristics of cultivated (left) and abandoned terraced slopes (right) in the study area.

On the right, examples a complete wall collapse are shown (red circle).

2.5 EXPERIMENTAL SITES

This research project, as previously illustrated in Paragraph 1.2.1, falls under the umbrella of the wider Stone Walls for Life project. The initial phases of this project primarily involved identifying suitable experimental sites for achieving the preliminary objectives, which focused on the detailed investigation of the differential response to precipitation events in terraced sites characterised by varying land use.

To achieve this objective, and based on meticulous observations and strategic considerations, the research activity within the LIFE project concentrated on identifying three specific experimental sites, located in the northern sector of the slope above the settlement of Manarola (Figure 2.16). The selection of these areas was guided by a series of methodological and logistical criteria aimed at optimising the study's scope.

Firstly, the accessibility of the sites was considered, a factor that significantly impacts field analysis operations and the installation of monitoring equipment. These aspects are crucial for the subsequent and accurate data collection.

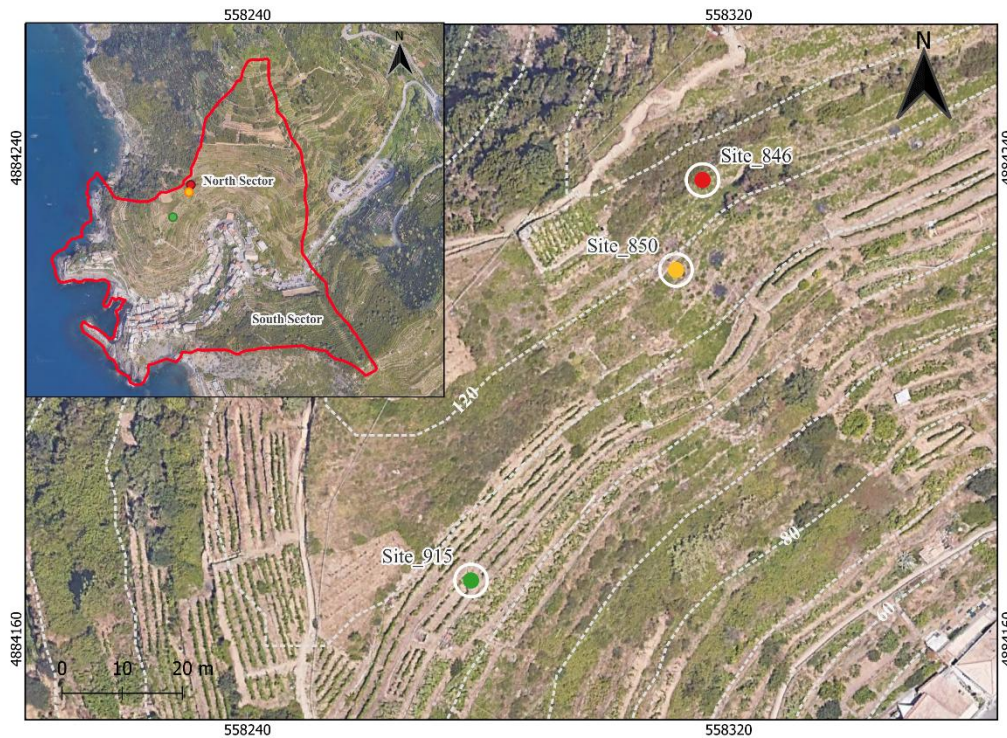


Figure 2.16 - Location of the experimental sites in the Manarola study area. The study area is delineated by the red polygon.

A crucial element in the selection of these sites is their capacity to represent the three primary land-use scenarios typical of the area, all encompassed within an area of just a few hectares. This allows for a direct comparison between different land management practices, summarized as follows:

Site 846: it represents a terraced area that has been abandoned for decades, providing an example of the ultimate stage affecting terraced slopes.

Site 915: it represents a terraced area under active cultivation. The dominant crop is a vineyard, which reflects the traditional agricultural practices of the region.

Site 850: it represents an abandoned terraced area since several decades, which has been restored by using traditional terrace building techniques; this site was deployed to study the initial phases of spontaneous revegetation after abandonment and its impact on stability.

The close proximity between the experimental sites is particularly advantageous for the instrumental setup, especially for the installation of the meteorological station. Indeed, this

station was strategically positioned at the centre of the investigation area; in this way, the acquired climatic data are highly representative for all three experimental sites.

Furthermore, the location of these experimental sites on the same slope offers optimal study conditions, as they show very similar geological and morphological contexts, thereby allowing for a consistent comparison of monitoring data.

2.5.1 Site 846

Site 846 constitutes an emblematic example of abandoned terraced structures within the Cinque Terre landscape. This experimental area was selected for its ability to comprehensively represent the long-term consequences following the cessation of anthropic management and maintenance activities. The abandoned site occupies the highest position along the slope, approximately at an elevation of 130 m a.s.l. (cadastral parcel 846).

The geometrical features of the site consist of a sub-horizontal terrace (approximately 24° slope) extending for about 10 m in length (length of the investigated segment) and 4 m in width. The superficial soil cover consists of reworked eluvial-colluvial soils. This deposit directly overlies an arenaceous bedrock belonging to the Macigno Fm.. The vegetation cover is dominated by spontaneous species, including brambles (*Rubus spp.*), gorse (*Genista spp.*), and shrubs, with the presence of larger trees such as holm oak (*Quercus ilex*).

The retaining dry-stone wall has an average height of approximately 1.9 m and an average width of around 50 cm. Its construction relies on the use of angular blocks of local sandstone, directly derived from the Macigno Fm. The distribution of block sizes (measured along the block major axis) appears almost homogeneous along the entire extent of the wall, ranging from a minimum of 5 cm to a maximum of 35 cm. The majority of the blocks fall within the 15 cm to 20 cm size ranges. The occlusion of the interstices between the blocks by fine-grained material constitutes a clear indicator of the state of aging of the wall structure. The selected dry-stone wall is affected by slight signs of deformation (e.g., bulges) while it does not show significative indicators and/or signs of incipient of collapse (Figure 2.17).



Figure 2.17 – Characteristics of the dry-stone wall terraced system at Site 846: 1) lateral view of the abandoned terraced area covered by spontaneous vegetation; 2) detail of the sandstone blocks constituting the wall; 3) monitored terrace section.

2.5.2 Site 915

Site 915 stands out as an example of a resilient agricultural practice outlined by the presence of the “*pergola*” type vineyards, a typical management practice for terraces that optimises farming production by mitigating the effects of adverse environmental conditions, especially the action of wind (Figure 2.18). Agricultural practices at this site are restricted solely to weed cutting, with all forms of soil tillage strictly excluded.

The terraced platform has a width of 4 m with an inclination of 17°. The soil cover consists of loose and/or poorly compacted coarse and anthropically reworked eluvial-colluvial deposits. This material rests directly on the arenaceous bedrock belonging to the Macigno Fm.

The retaining dry-stone wall has an average height of 1.7 m and an average width of approximately 50 cm. The masonry structure is characterised by the use of angular rock blocks. The presence of fine-grained material within the interstices between the blocks is a clear indicator of the structure's state of ageing and degradation. Furthermore, the blocks comprising the wall exhibit chromatic disuniformity, with a tendency towards a grey colour. This colour difference can be correlated with the presence of rocks that have not yet undergone the full process of weathering. This heterogeneity suggests that the stones were incorporated into the

structure at a time subsequent to the original construction, most likely during maintenance, restoration, or repair interventions on the wall. Over time, such interventions involved the replacement of damaged or deteriorated blocks or of partially collapsed sections of the wall (Figure 2.18). The arrangement of the blocks within the wall is heterogeneous. Indeed, block sizes (measured along the block major axis) vary significantly, with minimum measurements between 5 and 7 cm and maxima that can reach 45 cm. Most blocks exhibit a length ranging between 20 and 30 cm (Figure 2.18).



Figure 2.18 - Characteristics of the dry-stone wall terraced system at Site 915: 1) View of the terraced vineyard; 2) Details of the dry-stone wall structure and of the “*pergola*” type vineyard cultivation.

2.5.3 Site 850

Site 850 is representative of the intermediate condition between cultivated and decades-abandoned land-use scenarios. Indeed, during the investigated monitoring period, this site represents an initial stage of terrace abandonment, characterized by the growth of spontaneous vegetation, primarily weeds, reaching heights of 50-60 cm during the growing seasons.

The peculiarity of this site, compared to the others previously analysed, lies in the complete reconstruction of the dry-stone wall. The intervention in question was carried out as part of the STONE WALLS FOR LIFE project. As previously illustrated in Paragraph 1.2.1, the primary objectives of this project included the restoration and reconstruction of dry-stone walls that were in an advanced state of deterioration. For this reason, the terracing of Site 850 was included among the areas selected for dry-stone wall reconstruction, which was executed in

strict adherence to traditional building techniques. The dry-stone wall reconstruction involved the use of allochthonous blocks of unweathered sandstone-marly limestone. However, in some layers, rock blocks recovered in situ from the previous wall or found during preliminary construction operations were recycled. The reconstructed wall has a height of 1.8 m and an average width of 50-60 cm.

The terrace platform, which is located upslope of the wall, has an inclination of 13°, an approximate width of 3 m, and a lateral continuity of about 6 m. The topsoil is approximately two metres thick, resting on an arenaceous substratum belonging to the Macigno Fm. (Figure 2.19).



Figure 2.19 - Characteristics of the dry-stone wall terraced system at Site 850: 1) Lateral view of the terrace; 2) Frontal view of the new masonry rebuilt using traditional building methods; 3) Details of the different sandstone-marly limestone blocks forming the wall.

CHAPTER 3 – MATERIALS AND METHODS

3.1 MONITORING FRAMEWORK

The in-situ monitoring system is divided into two main components: a hydrological monitoring system and a mechanical monitoring system (Figure 3.1).

Hydrological Monitoring: for the characterisation of hillslope hydrological, instrumentation capable of monitoring key parameters was installed. This installation provides an essential dataset for understanding soil hydrological responses to climatic events and water movement within the hillslope profile. Specifically, this instrumentation includes soil water potential sensors, soil moisture sensors, and a weather station.

Mechanical Monitoring: this approach enables the detection of lateral pressures induced by the soil mass on the wall and their temporal variations in response to changes in hydrological conditions, providing crucial information on the structural stability of the terraced areas. Specifically, total pressure cells have been installed, between the backfill soil and the wall, which directly measure the total stresses exerted by the ground.



Figure 3.1 - Location of the three monitoring sites, presented in both planimetric and oblique view.

Hydrological monitoring was implemented across all three investigation sites to acquire a comparative overview of hydrological responses under different land-use conditions while mechanical monitoring was carried out exclusively at Site 850 (Figure 3.2).

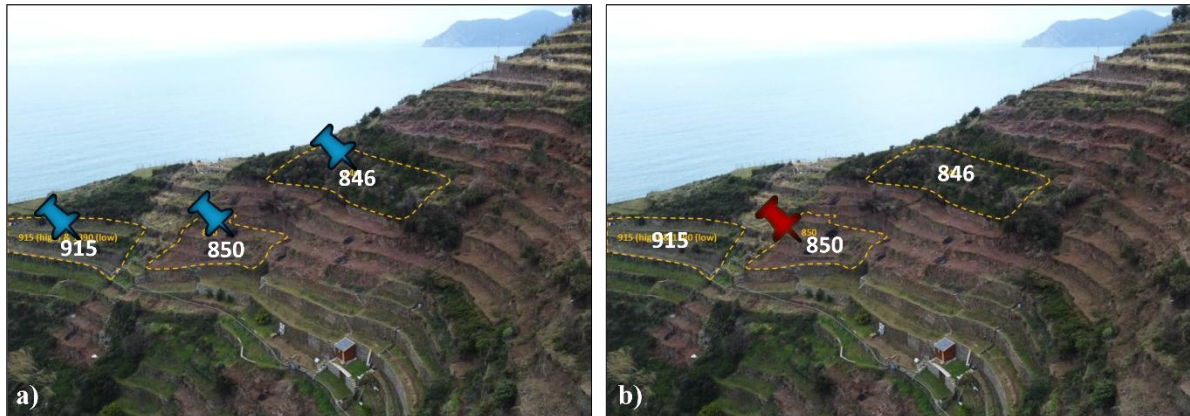


Figure 3.2 – Location of monitoring sites: a) blue symbols indicates the sites where hydrological sensors were installed; b) red symbol shows the site where mechanical monitoring instruments were installed.

3.1.1 Water potential sensor

To measure soil matric potential, the TEROS 21 sensor (METER Group), designed for continuous, long-term field measurements and for being maintenance-free, was used.

The sensor is based on the principle of frequency domain reflectometry (FDR) dielectric measurement coupled with a porous matrix. It consists of two engineered porous ceramic discs, each with a specific water retention curve, and of a capacitive sensor that measures the dielectric constant of the porous material (Figure 3.3).



Figure 3.3 - Structure of the TEROS 21 Sensor (METER Group 2021a).

The TEROS 21 sensor primarily allows for the measurement of two key soil parameters:

- **Soil Matric Potential (Ψ_m):** this parameter, typically expressed in kiloPascal (kPa), represents the energy with which water is held in the soil by matric forces (i.e., adhesion and capillarity). It is a direct indicator of water availability for plants and the direction of water movement within the soil profile. Unlike volumetric water content alone, matric potential is independent of soil type (within certain limits) for a given retention curve, allowing for meaningful comparisons between sites with different textures.
- **Soil Temperature (T):** temperature measurement is essential for compensating thermal influence on water potential and for more complex thermo-hydraulic studies. The sensor operates within a typical range of -40°C to $+60^{\circ}\text{C}$.

The operating principle is based on the equilibrium between the water potential of the surrounding soil and that one within the ceramic matrix. When the sensor is installed in the ground, water moves between the soil and the ceramic until the water potential equalises. At this point, the sensor measures the water content of the ceramic matrix via its dielectric constant. By knowing the water retention curve of the ceramic (calibrated in the laboratory) (Figure 3.4), the measured water content is converted into the soil matric potential.

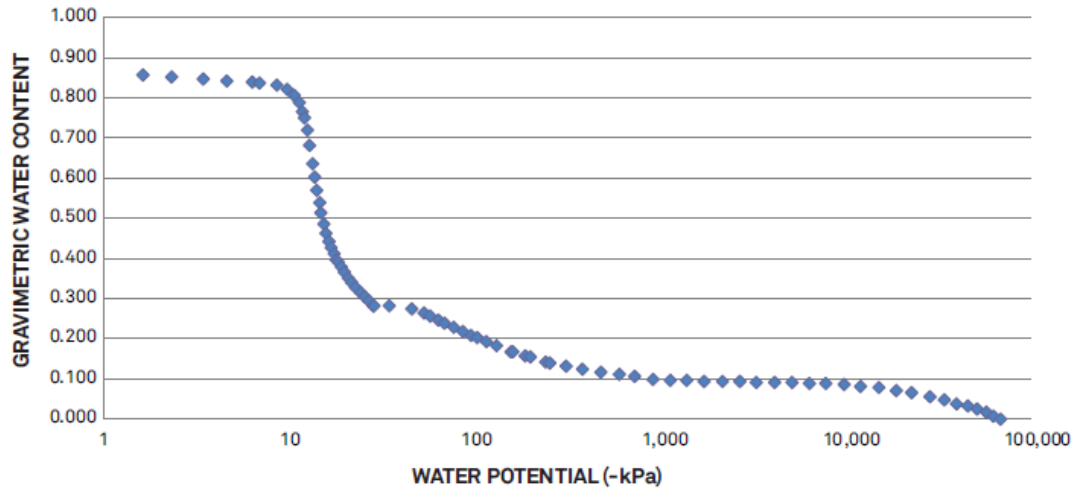


Figure 3.4 - Moisture characteristic curve of TEROS 21 ceramic derived from mercury porosimeter data (METER Group 2021a).

The TEROS 21 sensor is manufactured to be robust and durable, suitable for harsh environmental conditions and for long-term monitoring. The sensor features an epoxy overmolding that makes it resistant to the most extreme field conditions, ensuring a long operational life. Furthermore, the porous ceramic discs are designed with a wide pore size distribution, which significantly extends the measurement range of water potential compared to sensors based on ceramics with more uniform porosity. These materials do not degrade and do not require periodic recalibrations in the field.

The instrument has a length of 9.6 cm, a width of 3.5 cm, and a diameter of 3.2 cm, dimensions that facilitate its *in-situ* installation at various depths (Figure 3.4). Its rapid response is ensured by a 150 ms measurement interval, allowing for near real-time acquisition of water potential variations. The dielectric measurement frequency is 70 MHz, a value that contributes to the accuracy of the dielectric constant readings of the porous medium (METER Group, 2021a).

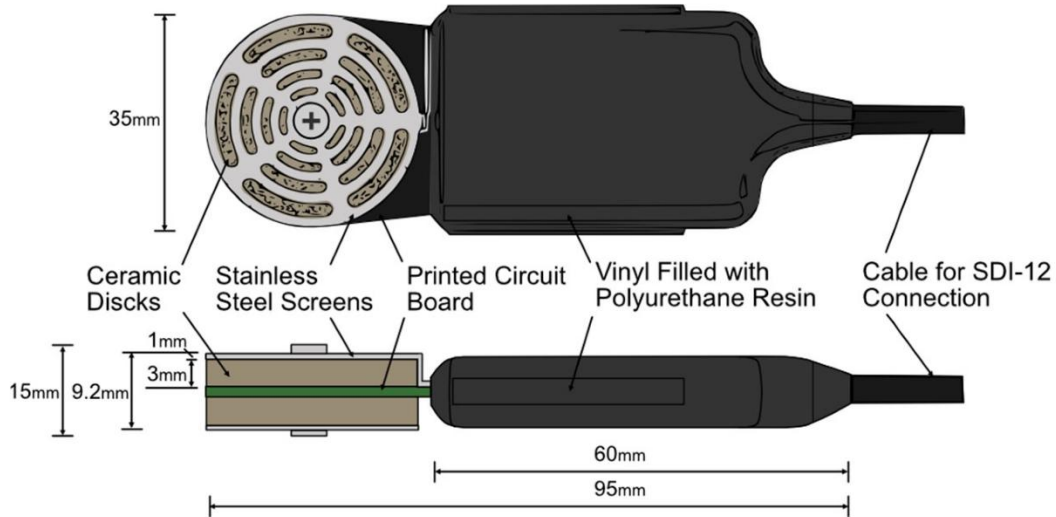


Figure 3.4 - Detailed technical scheme of the TEROS 21 soil water potential sensor, illustrating its key components and dimensions in both plan and cross-sectional views (Stasi et al., 2025).

The TEROS 21 sensor has been specifically designed to cover a wide range of water potential measurements, spanning from conditions close to soil saturation, approximately -5 kPa, to states of extreme drought, corresponding to very low potentials, close to the permanent wilting point or dry air, reaching values up to -100,000 kPa. This extended range makes it suitable for monitoring both moist and arid soils. The sensor's resolution is 0.1 kPa, ensuring considerable sensitivity in detecting even small variations in water potential. Furthermore, the sensor transfers information externally via an SDI-12 connection cable. The SDI-12 connection in the TEROS 21 sensor is a standardised serial communication protocol used to interface sensors with data loggers and data acquisition systems (METER Group, 2021a).

Despite its advantages, the correct functioning of the TEROS 21 is strongly dependent on the quality of its installation. In particular, optimal contact between the sensor's ceramic matrix and the surrounding soil is crucial for obtaining accurate readings. Inadequate contact can lead to imprecise measurements, especially in soils characterised by high sand content or the presence of coarse fragments (skeleton), which can create air voids around the sensor. To mitigate this risk and ensure the reliability of readings, it is highly advisable to prepare a "paste" or slurry of soil and water for use at the time of installation. The application of this paste ensures that the sensor is completely enveloped by fine soil, maximising the contact area and facilitating hydrological equilibrium between the sensor and the soil (METER Group, 2021a).

3.1.2 Soil moisture sensor

To measure volumetric water content (VWC) and soil temperature, the TEROS 11 sensor, manufactured by METER Group was used. It consists of a frequency domain/capacitance sensor based on the relationship between the apparent dielectric constant of the medium (soil) and its water content.

The TEROS 11 sensor features a main body made of dark epoxy resin, which gives it a solid appearance and significant resistance to weathering and aggressive soil conditions. This structure has three stainless steel needles, approximately 5.5 cm in length, sharpened to facilitate penetration into the soil without causing excessive disturbance. Two of these needles are positioned laterally, while a third, slightly shorter, is located centrally (Figure 3.5).



Figure 3.5 - Structure of the TEROS 11/12 Sensor (METER Group, 2021b).

The TEROS 11 allows for the measurement of:

- **Volumetric Water Content (VWC):** represents the percentage of soil volume occupied by water.
- **Soil Temperature:** temperature across the soil profile.

The operating principle of the TEROS 11 sensors is based on capacitance/frequency domain technology operating at 70 MHz, which is chosen to minimise the effects due to soil texture and salinity, ensuring accuracy in most mineral soils.

Soil is a complex mixture of solid particles, water, and air. Each of these components has a different dielectric constant: water ~ 80 , solid particles 2-5 (varies depending on composition), and air 1. Since water has a significantly higher dielectric constant than the other components, even small variations in soil water content cause large variations in the apparent dielectric constant (ϵ_a) of the entire medium (METER Group., 2021b).

The operation of this instrument is founded precisely on this basic principle. Specifically, the stainless-steel needles (probes) are inserted into the soil. These needles act as electrodes of a capacitor. When the sensor is powered, it generates a high-frequency electromagnetic field (70 MHz) that extends into the volume of soil surrounding the probes (METER Group., 2021b).

Water, having a much higher dielectric constant (approximately 80) compared to soil solid particles (2-5) and air (1), significantly influences the apparent dielectric constant of the medium. The TEROS 11 sensor's microprocessor calculates the charging time and derives a raw value that depends on the dielectric constant of the material it is inserted into. Subsequently, this raw value is transformed into VWC using a specific calibration equation (METER Group., 2021b).

In terms of dimensions, the sensor has a length of approximately 9.4 cm, a width of about 2.4 cm, and a height, including the needles, of approximately 7.9 cm (Figure 3.6).

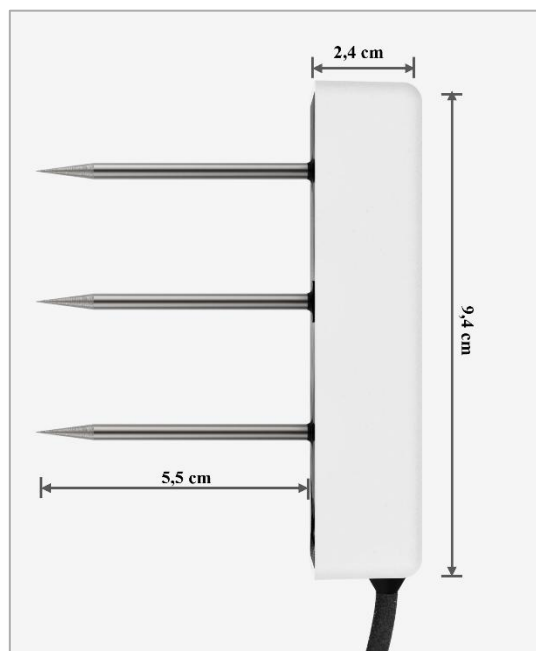


Figure 3.6 - TEROS 11 sensor technical details (METER Group, 2021b).

The VWC measurement ranges are broad: from 0.00 to 0.70 m^3/m^3 (0-70% VWC) with calibration for mineral soils, and further to 0.0 – 1.0 m^3/m^3 (0-100% VWC) for soilless

substrates. The measured apparent dielectric permittivity (ϵ_a) varies from 1 (air) to 80 (water). Temperature is detectable from -40 °C to +60 °C (METER Group., 2021b).

A typical accuracy of $\pm 0.03 \text{ m}^3/\text{m}^3$ ($\pm 3\%$ VWC) is recorded with generic calibration in mineral soils, which improves to $\pm 0.01\text{--}0.02 \text{ m}^3/\text{m}^3$ ($\pm 1\text{--}2\%$ VWC) with specific medium calibration. The sensor operates at a dielectric measurement frequency of 70 MHz. The time required for a single measurement is approximately 25 ms.

Connection to the data logger is made via a robust 3-conductor cable. The standard length is 5 metres, which is fundamental for power supply and data transmission. Communication between the sensor and the data logger also occurs, in this case, via the SDI-12 digital protocols.

A significant advantage of this sensor is the ease of installation. This aspect is crucial for minimising the formation of air voids around the sensing elements.

3.1.3 Tangential and radial pressure cells

The Tangential and Radial Pressure Cells are instruments used in the field of geotechnical and structural monitoring. They are fundamental for measuring the opposing action between two adjacent surfaces, detecting the stress state and the total pressures that the surface, ground, or material exert on the cell.

Rectangular hydraulic cells, also known as NATM (New Austrian Tunnelling Method) cells, were used to monitor the tensional states on dry-stone walls. This device consists of two rectangular stainless-steel plates (width 100 mm and length 200 mm), soldered at the edge to form an iron interspace, which is filled with deaerated oil and connected by a stainless-steel tube to an electric pressure transducer. In particular, at the lower end of the cell, there are two connectors. One connector is used for the initial filling, i.e., to fill the cell's internal cavity with de-aired oil under vacuum during production (Figure 3.7). This ensures no air is inside, which could compromise measurement accuracy. The second connector links the cell's internal cavity to the pressure transducer (Figure 3.7). This second tube features a manometer at its end for re-pressurisation operation (Pizzi Instruments, 2020) (Figure 3.7).

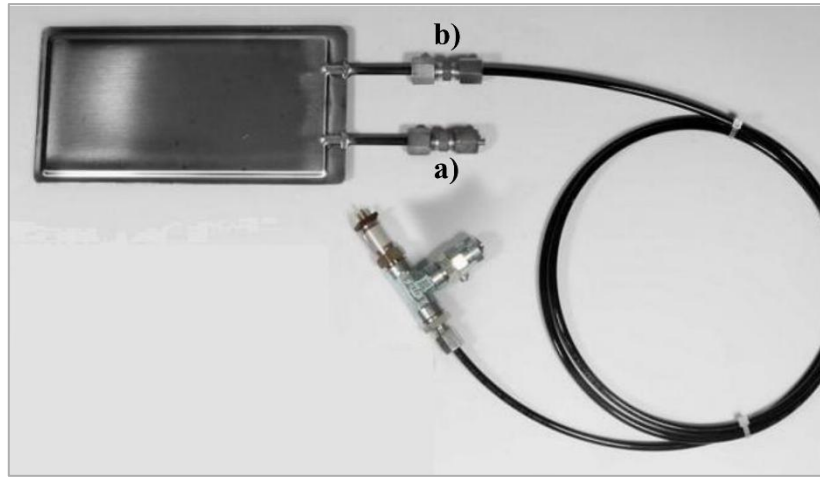


Figure 3.7 - Structure of tangential and radial pressure cells. a) Initial pressure tube; b) re-pressurization tube where the pressure gauge is inserted at the end (Pizzi Instruments S.r.l.).

The operating principle is based on pressure transmission; that is, the two steel plates receive the load exerted by the adjacent ground or structure, which in turn is transmitted to the de-aired oil. The oil transmits the pressure through a small tube (usually stainless steel) to an electrical pressure transducer which converts it into an electrical output signal (mA), proportional to the pressure.

The pressure cells were calibrated by the manufacturer within a measurement range of 0 to 10 bar. Figure 3.8 shows the calibration graphs, which illustrate the relationship between the electrical output signal from the pressure cell and the applied pressure. The calibration graph thus serves as a conversion key, essential for the accurate interpretation of the raw data.

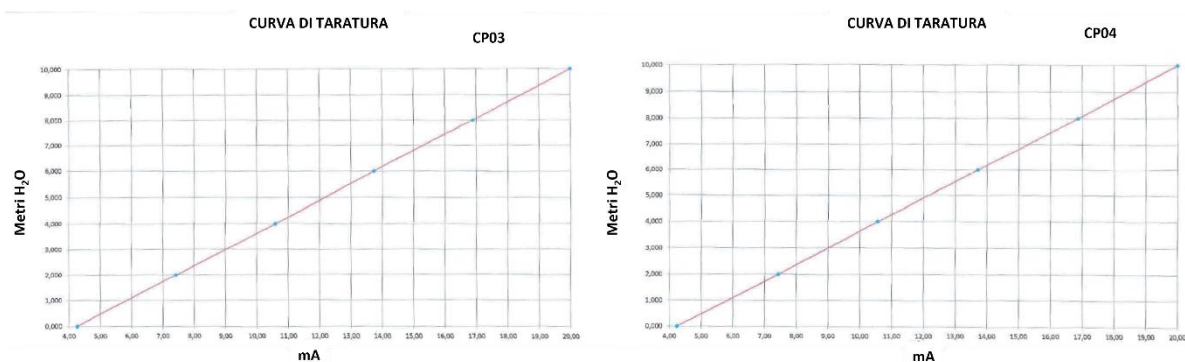


Figure 3.8 - Manufacturer-issued calibration certificates for the installed pressure cells.

The overall accuracy remains below 0.35% of the Full Scale (F.S.) while the operating temperature is typically between -20°C and +60°C, or in some cases, between -20°C and +80°C (Pizzi Instruments S.r.l., 2020).

One of the most critical aspects of this device is the necessity of a vacuum filling with de-aired oil, requiring extreme care during re-pressurization to prevent the formation of air bubbles within the system, which could seriously compromise measurement accuracy. Another limitation is temperature dependence: although designed to operate within a specific temperature range, extreme variations can affect their performance, sometimes necessitating compensation.

3.1.4 Weather station

The installation of a weather station aims to monitor precipitation and other essential atmospheric parameters to investigate the soil's hydrological behaviour which, in synergy with other instrumentation, allow to evaluate the evapotranspiration flux (Figure 3.9).

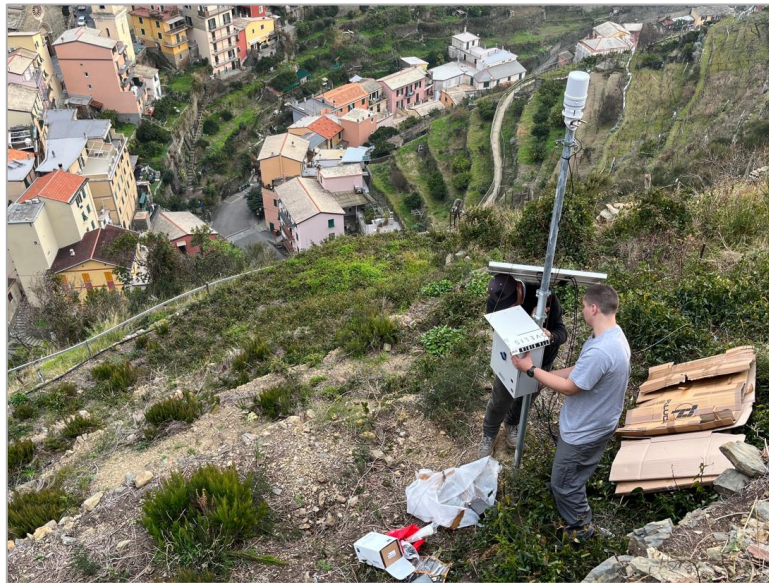


Figure 3.9 - Weather station installed in the study area.

Weather measurements are accomplished with the ATMOS 41 all-in-one station (METER Group 2021c), which is equipped with various instruments which are integrated into a single, small form-factor unit:

- Resistance Thermometer: it measures air temperature, recording maximum and minimum values and calculating their average for a given period (measurement returned in °C).
- Barometer: for the measurement of atmospheric pressure, providing the maximum and minimum values recorded during the monitoring period (measurement returned in hPa).

- **Hygrometer:** it measures the relative humidity of the air, also reporting the maximum and minimum values for the period under examination. Measured in %, this value expresses the ratio between the actual amount of water vapour present in the air at a given moment and the maximum amount of water vapour the air could contain at the same temperature and pressure.
- **Anemometer and Wind Vane:** the anemometer measures wind speed (measured in m/s), while the wind vane indicates its direction (measured in °).
- **Rain Gauge:** it allows for the measurement of both the quantity of precipitation (expressed in mm) fallen within a specific time interval and its intensity (expressed in mm/h).
- **Solar Sensors:** for the measurement of solar radiation (measured in W/m²).

The measurements specifications of each mounted weather sensor are summarized in Table 3.1.

Table 3.1 - All-in-one ATMOS 41 weather station sensors measurement specifications

	Range	Resolution	Accuracy
Solar radiation	0-1750 W/m ²	1 W/m ²	±5% of measurement typical
Precipitation	0-400 mm/h	0.017 mm	±5% of measurement from 0 to 50 mm/h
Vapor pressure	0-47 kPa	0.01 kPa	Varies with temperature and humidity
Relative humidity	0-100% RH	0.1% RH	Varies with temperature and humidity
Air temperature	-50 to 60 °C	0.1 °C	±0.6 °C
Humidity sensor temperature	-40 to 50 °C	0.1 °C	±1.0 °C
Barometric pressure	1-120 kPa	0.01 kPa	±0.05 kPa at 25 °C
Horizontal wind speed	0-30 m/s	0.01 m/s	The greater of 0.3 m/s or 3% of measurement
Wind direction	0°-359°	1°	±5°

Data acquisition occurs through a structured process. Each meteorological parameter is detected by a specific sensor that converts physical quantities into electrical signals. These signals are subsequently transmitted to a data logger. The data logger is responsible for the digitalisation, processing, calibration, and storage of analogue signals at predefined time intervals, in this case, on an hourly basis. The station's operational autonomy, even in the absence of access to the electrical grid, is guaranteed by rechargeable batteries powered by solar panels. Data stored in the data logger are accessible and can be retrieved via specific management software. The signals coming from the above-described sensors are acquired by a CR310 datalogger

(Campbell Scientific, Inc.) supplied by a gelatin-based hydrogel electrolyte battery, which in turn is powered by a photovoltaic panel.

3.1.5 Installation procedures

In the subsequent sections, a detailed description of the installation procedures followed for each type of instrument in each experimental site is described.

Prior to installation, a thorough site evaluation was conducted to identify optimal installation points, considering geomorphological specificities (slopes, slope morphology), hydrogeological features (presence of preferential flow paths), and land use (vegetation type). This was done to select area representative of the expected hydrological and geotechnical conditions. Based on these considerations, three representative installation sites were identified (Figure 3.10).

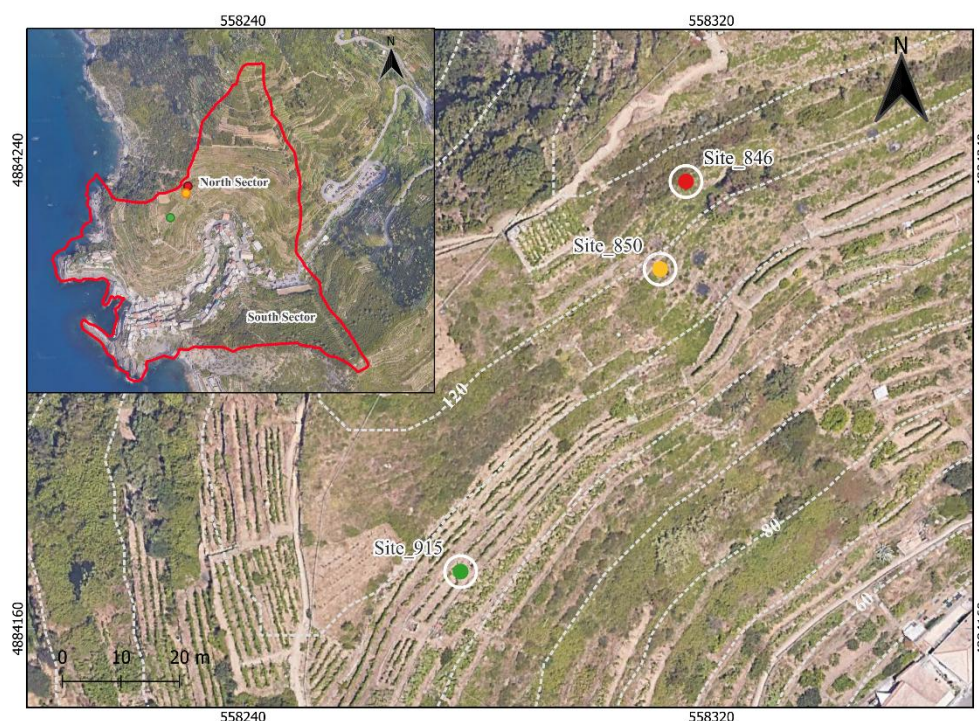


Figure 3.10 - Location of the three experimental monitoring sites.

For each investigation site, the instrumentation was positioned on the terrace platform uphill of the reference dry-stone wall (Figure 3.11).

A trench approximately 50-60 cm wide and 120-150 cm long was excavated. Trenches were excavated approximately in the middle of the terrace tread. Based on the consistent outcomes of the engineering-geological investigations, approximately 0.9-1.0 m deep trenches were excavated (Figure 3.13). Specifically, the excavation depth was determined according to the

depth required to reach the weathered bedrock for each specific site. To minimise the alteration of the surrounding natural soil structure, the excavation was performed exclusively using manual tools. The dimensions of the trench were chosen to ensure straightforward instrument installation and a subsequent effective and coherent restoration of the ground.



Figure 3.11 - The yellow arrow indicates the area upstream of the retaining wall, where the sensors were installed for each experimental monitoring site.

The depths of the sensor installation were chosen based on the soil stratigraphy visible along the trench sidewalls. To ensure optimal hydraulic contact between the TEROS21 sensor and the surrounding ground, some excavated native soil was moistened to achieve a better interaction with the sensor's ceramic surfaces. To this purpose, a hydraulic contact matrix was prepared around the sensor by using the finer fraction of the native soil (obtained through sieving) mixed with water. The resulting compound was then carefully packed around the sensor (Figure 3.12).



Figure 3.12 - Preparation of a fine material and water slurry which was packed around the TEROS21 sensor.

Subsequently, to insert the instrument into the trench wall, a knife was used to remove a small portion of soil, creating a small pocket into which the sensor was inserted, ensuring the soil was well compacted around it. During installation, care was taken not to embed the sensor close to roots. Once the sensor was inserted into the ground, its cable was protected by enclosing it into a protective sheath (flexible PVC tubing) up to the connection point with the datalogger. This protection is essential to prevent damage from animals, agricultural equipment, or atmospheric agents.

Similarly, volumetric water content sensors (i.e., TEROS 11) require optimal contact between the instrument and the soil.

Accordingly, considering a homogeneous vertical side of the trench, the sensor was inserted (with a horizontal orientation) by pushing it into the undisturbed ground being careful to avoid roots or pebbles that could potentially bend the needles or affect both the sensor functioning and readings.

Upon completion of the entire sensor installation, the soil removed during excavation was meticulously backfilled to preserve as much as possible the native bulk density and the previous soil stratigraphy. This operation minimises any alteration to the natural water flow within the soil profile.

At site 915 the pairs of TEROS 11 and TEROS 21 sensors was positioned at depths of approximately 20, 30 and 50 cm, while at sites 846 and 850 at depths of approximately 30, 50 and 70 cm (Figure 3.13 and Table 3.2). At Sites 850 and 846, sensors were strategically

positioned on the downslope-facing (or valley-oriented) trench wall. This placement was specifically designed to detect the ingress of water originating upslope and moving towards the wall. The sole exception to this arrangement is Site 915, where the monitoring instruments were installed upslope of the trench. This alternative approach was necessitated because the morphological irregularity of the excavation face precluded the possibility of installing the sensors directly onto the wall.

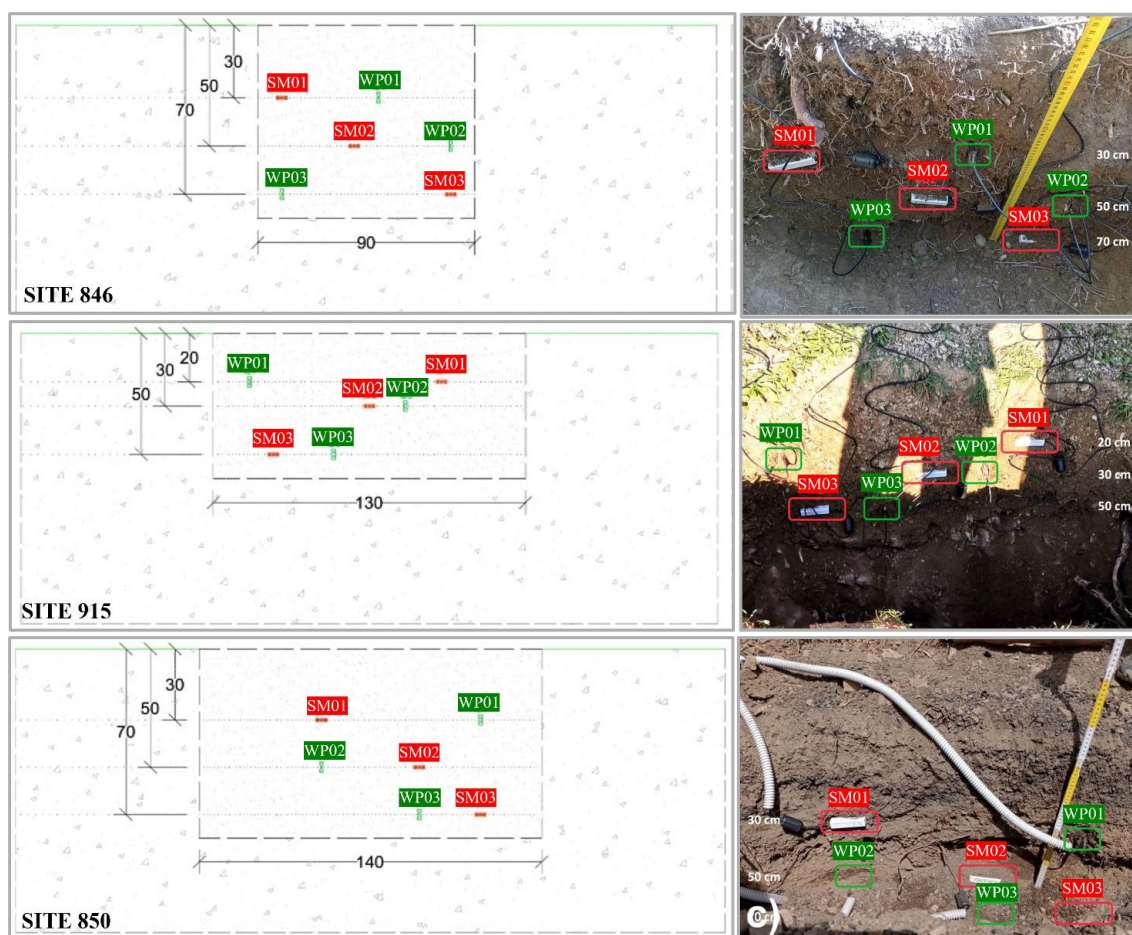


Figure 3.13 - Sketch and arrangement of soil hydrological sensors within trench pits dug in each study site.

Table 3.2 - Overview of the key installation features for the monitoring equipment at each study site. SM: Soil Moisture (sensor), WP: Water Potential (sensor), Tr_L: Trench Length and Tr_D: Trench Depth.

	Installation Date	Tr_L cm	Tr_D cm	SM_Sensor_Depth			WP_Sensor_Depth			Root_Depth cm
				SM01 cm	SM02 cm	SM03 cm	WP01 cm	WP02 cm	WP03 cm	
St_846	16/02/2023	90	≈ 80	30	50	70	30	20	70	70
St_915	16/02/2023	130	≈ 90	20	30	50	20	30	50	50
St_850	02/08/2023	150	≈ 70	30	50	70	30	50	70	20

All sensors were connected to a datalogger for automatic data acquisition powered by a photovoltaic panel (Figure 3.14).



Figure 3.14 - Multiparametric monitoring systems and dataloggers installed at each monitoring site.

Eventually, the weather station was installed approximately in a central position relative to the three experimental sites to ensure that the collection of representative meteorological data (Figures 3.15 and 3.16).

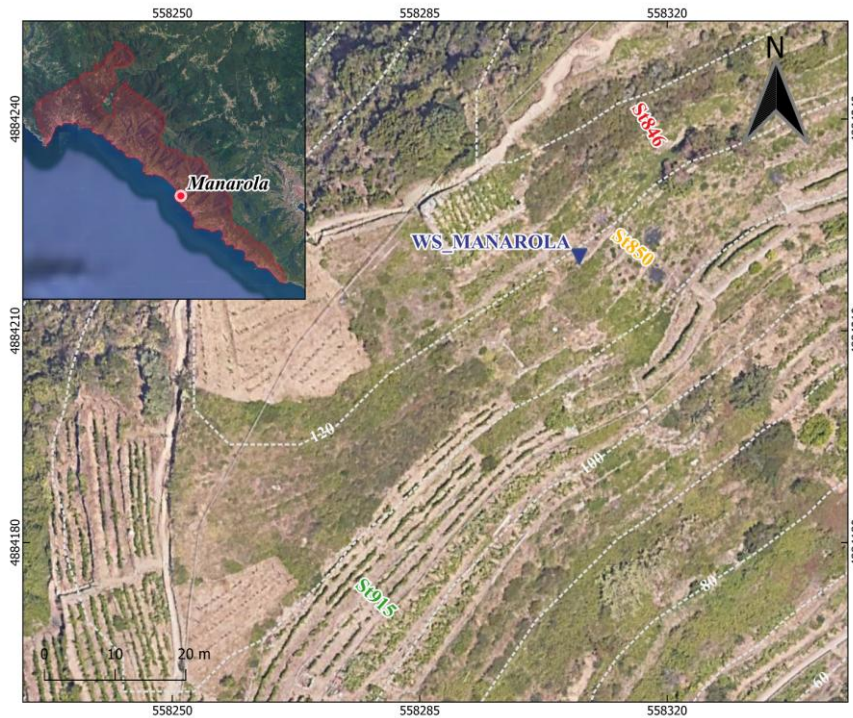


Figure 3.15 - Location of the weather station.

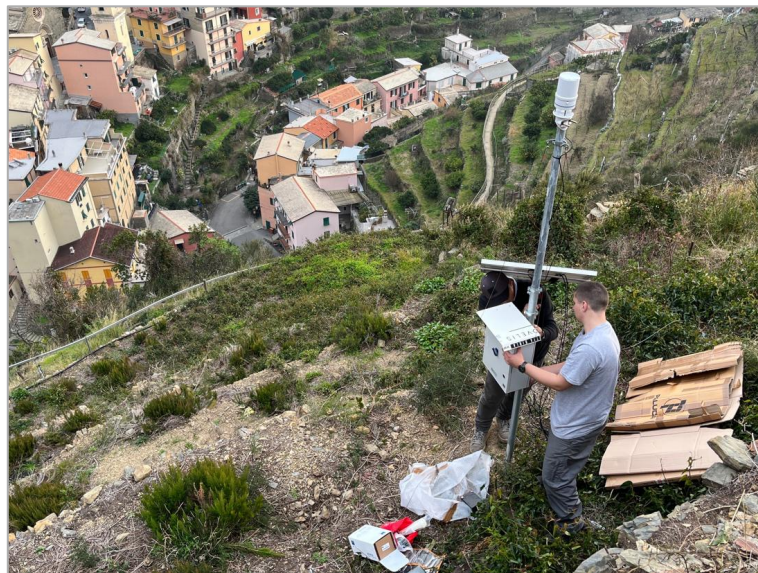


Figure 3.16 - Installation of the weather station.

Finally, at site 850 the installation of the pressure cells behind the wall was undertaken, with the aim of monitoring the total pressures that develop behind the wall due to soil thrust.

The initial phase of pressure cell installation involved the creation of the base layer, i.e., the wall's foundation. This foundation was laid directly on the bedrock, as illustrated in Figure 3.17. The tabular rocks used for the foundation had approximate dimensions of 50-70 cm in length and approximately 50 cm in width (Figure 3.17).



Figure 3.17 - Excavation operations placement of rock blocks for the wall's foundation on the weathered bedrock.

Two cells (i.e., CP03 and CP04) was arranged immediately behind the wall with the flat surfaces oriented vertical. The lower sides of the cells were positioned on a thin layer of non-shrink sand cemented grout and then sealed. The free part of the cell plate was covered with an additional layer of mortar (Figure 3.18). Uniformity and absence of discrepancies in the cells' positioning were verified using a spirit level, as shown in Figure 3.18.



Figure 3.18 – Installation of pressure cells behind the wall.

During the construction, the space immediately behind the stone blocks of the wall was progressively filled with coarse-grained soil material and pebbles to promote drainage (Figure 3.19). The backfill of the terrace was progressively created using native soil which was sieved

on site to remove large pebbles and cobbles. Eventually, the geometry of the terrace tread was restored in order to keep the surficial water flows as much as possible in their original condition.



Figure 3.19 - Detail of the backfill material used during wall construction.

Two pressure cells were placed at a height of 10 and 90 cm from the dry-stone wall foundation, respectively (Figure 3.20).

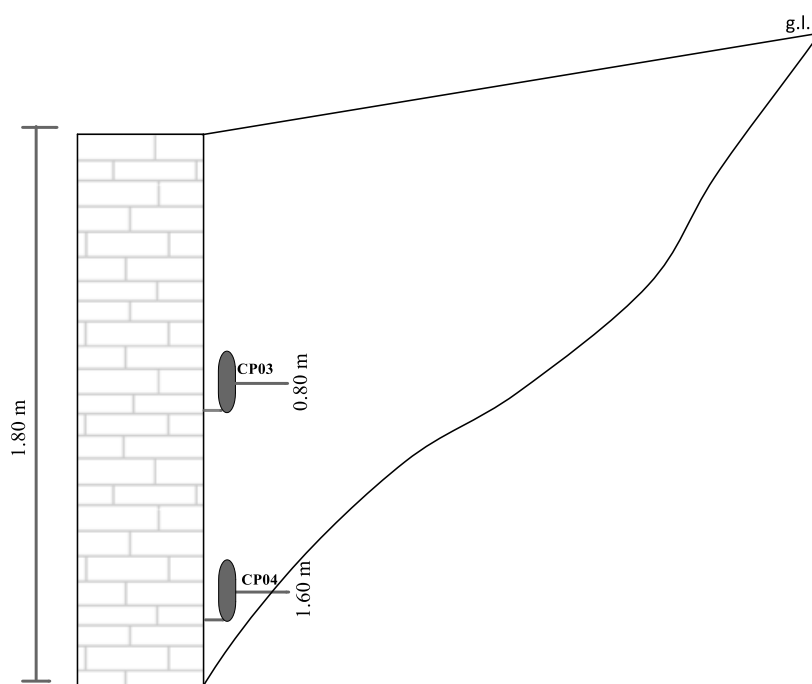


Figure 3.20 – Sketch of the installed pressure cells.

3.2 SLOPE-SCALE STABILITY ANALYSIS

To delineate a preliminary overview on the stability conditions of the selected terraced area, a slope-scale stability analysis was conducted. This analysis was carried out using a detailed engineering-geological model, based on the results of laboratory and in-situ investigations, made available by the “Stone wall for life” project. This approach allowed for a general evaluation of the various factors (e.g., geotechnical and morphological variables) mostly conditioning the overall terraced slope system response. In particular, the attention was focused on three key aspects: i) the variation in soil cohesion attributable to the contribution of vegetation; ii) the morphological characteristics of the terraced slope and iii) the influence of the stratigraphic setting.

3.2.1 Strength reduction stability analysis - ADONIS

The ADONIS software was used, which is a numerical calculation tool based on the Finite Element Method (FEM) (Mikola, 2017), a technique widely used in the modelling of geotechnical behaviour of soils and structures.

The FEM is a discrete numerical method used to solve partial differential equations that govern complex physical problems for which direct analytical solutions do not exist. The fundamental principle consists of dividing a continuous domain of interest into a finite set of sub-domains, known as finite elements, which are interconnected at discrete points called nodes. The primary unknown variables of the problem (e.g., displacements in stability analysis) are associated with each node. The method proceeds by formulating the governing equations for each individual element, then assembling them into a global stiffness matrix that represents the entire system. The assembly process is guaranteed by the continuity of the variables at the nodes shared between adjacent elements. The solution of this large system of linear equations simultaneously provides the values of the unknown variables for all nodes in the domain. In summary, the FEM transforms a continuous problem (e.g., the stress field distribution) into a discrete algebraic problem, approximating the solution with a high degree of precision.

Within the ADONIS software, the Strength Reduction Method (SRM), an advanced numerical technique used in the field of soil mechanics and geotechnics to evaluate slope stability, is implemented. SRM simulates the evolution of the stress and deformation state of a slope starting from an initial equilibrium configuration. This is achieved through a progressive and controlled reduction of the shear strength parameters of the geotechnical materials.

SRM operates iteratively reducing the soil's shear strength parameters (i.e., effective cohesion (c') and friction angle (ϕ') by Strength Reduction Factor (SRF). This process continues until the slope's failure condition is reached, which is identified by the divergence of the numerical solutions. The Factor of Safety (FOS) of the slope is then defined as the value of the SRF at failure.

SRF is directly implemented in the equations of the Mohr-Coulomb failure criterion, which describes the stress conditions under which a cohesive and frictional material reaches failure as follows:

$$\tau_f = c' + \sigma_n' \tan(\phi') \quad (1)$$

where τ_f is the shear strength at failure, c is the effective cohesion (i.e., the intercept at the linear failure envelope), σ_n' is the effective normal stress on the failure plane, and ϕ' is the effective friction angle.

This equation indicates that soil shear strength increases linearly with an increase in normal stress. The cohesion (c') represents the material's shear strength even in the absence of normal stress (for example, a clay soil). The angle of friction (ϕ') describes the resistance due to friction between the material's grains.

By applying the SRF to the Mohr-Coulomb equation, we obtain:

$$\tau_f = \frac{c_{in}}{SRF} + \sigma_n' \tan \left(\arctan \left(\frac{\tan(\phi_{in})}{SRF} \right) \right) \quad (2)$$

where c_{in} and ϕ_{in} are the initial effective cohesion and friction angle, respectively.

Before applying the SRF, the software performs an initial geotechnical analysis to determine stress and strain states under original static conditions, without any reduction to the strength parameters. This calculation represents the starting point for the subsequent analysis.

Subsequently, ADONIS performs an iterative calculation cycle by step-by-step reducing the shear strength parameters using an incremental SRF, thus simulating a progressive soil weakening. The software seeks a new equilibrium by progressively reducing strength parameters until failure occurs, namely when the mobilised shear strength is no longer sufficient to resist the stresses, leading to failure.

The SRF value at failure corresponds to the FOS (if equal to 1 indicates a limit equilibrium condition, while values greater than 1 indicate stability).

3.3 DETAILED-SCALE ANALYSIS METHOD

The results of the global analysis guided the research towards a detailed study of individual dry stone wall terrace systems, with a specific focus on the hydrological dynamics developing through the backfill materials, which can critically influence the local instability.

To characterise the system responses, conceptual and numerical hydrological models were developed for each experimental site that were calibrated and validated using in-situ monitoring data. These models were implemented and subjected to rigorous validation within the GeoStudio simulation environment, specifically employing the SEEP/W module for modelling transient water flow under unsaturated conditions. The flow analysis was conducted to quantify the variation in hydrological dynamics and pore-water pressures within the subsurface profile in response to external hydrological stresses. This process is crucial for defining the influence of boundary conditions on the variation of the system intrinsic hydrological characteristics. The results obtained from the flow modelling (i.e., the spatial and temporal distribution of pore-water pressures) were subsequently transferred as input variables for the slope stability analysis, which was conducted according to the limit equilibrium principle using the SLOPE/W module. The primary objective of this integrated modelling approach is the assessment of the variation of the critical factor of safety (SFc) as a function of changes in the soil hydrological conditions as well as in the site-specific geometrical and geotechnical properties (i.e., slope geometry, gradient, and thickness of the superficial cover).

3.3.1 Theoretical background on unsaturated soil behaviour

The primary difference between saturated soil and unsaturated soil lies in the composition of the voids within the soil matrix, which has fundamental consequences for their mechanical and hydrological properties.

A soil is defined as saturated when all the voids between the solid particles are completely filled with water, involving a degree of saturation of 100%. Within the soil, the water exerts a positive pressure, known as pore water pressure (u_w), which reduces the effective stress between the soil grains.

In contrast, in an unsaturated soil the voids between the particles contain both water and air, thus involving a degree of saturation ranging between 0% and 100%. In this case, the water within the pores is under pressure that is less than that of the air ($u_w < u_a$), and this pressure difference is called suction. Suction acts as a surface tension force that holds soil particles together, creating an apparent cohesion that can significantly increase the soil's shear strength.

The main process that causes a soil to become unsaturated is the loss of water from its pores, which occurs when water is removed at a faster rate than it is replenished. This process, which involves a change in the mechanical and hydrological behaviour of the soil, generally occurs in the upper zone of the ground (i.e., vadose zone) above the water table due to evaporation from the ground surface (Figure 3.21) and a lowering of the groundwater table.

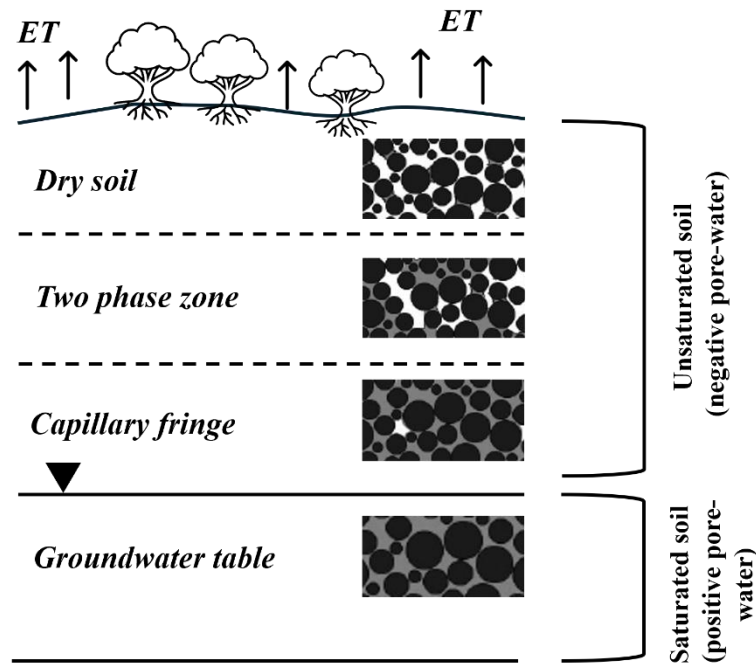


Figure 3.21 - Transition from saturated to unsaturated soil conditions (ET: evapotranspiration).

This process can be effectively explained using the analogy of a capillary tube system, which replicates the behaviour of water in the porous spaces of geomaterials (Figure 3.22). Initially, the soil is fully saturated. Therefore, the air-water interface is flat as the adhesive forces (between the liquid and the tube surface) and cohesive forces (between the liquid molecules themselves) are in equilibrium. Consequently, the water pressure is equal to the atmospheric pressure ($u_w = u_a$).

Following evapotranspiration, water is initially removed without any significant change in the solid-liquid-gas contact angle (θ). This leads to an increase in the curvature of the air-water contact surface (the meniscus), as the adhesive forces become greater than the cohesive forces. As a result, the water pressure inside the capillary tube (and thus in the pores) drops to values below atmospheric pressure. Evaporation continues until the meniscus contact angle reaches a maximum value, known as the receding contact angle (θ_r). At this stage, the liquid pressure reaches the minimum value that the meniscus can sustain. This critical pressure value, which is

less than atmospheric pressure, is defined as the *air entry pressure*. When this pressure is reached, air begins to enter the capillary tube (i.e., the soil pores). From this point on, any further loss of water due to evaporation does not cause an additional decrease in pressure; instead, it results in a progressive lowering of the meniscus and an increase in the gas phase within the pore. At this stage, the soil begins its desaturation process, where the negative pore water pressure effectively represents the suction present in the soil.

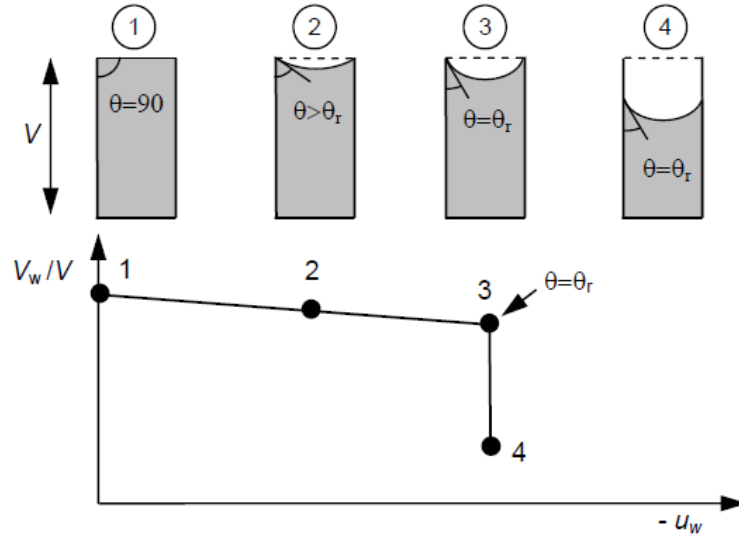


Figure 3.22 - The process of soil desaturation through evapotranspiration, as represented by individual capillary tubes (from Tarantino, 2010).

Schematizing soil as a series of interconnected capillary tubes is an effective model for describing the behaviour of water within it. The size of these "tubes" (i.e., the pores), which varies with the soil's granulometry and gradation, influences the desaturation process. Therefore, the relationship that governs the variation of negative pressure (suction) with pore size is described by the Young-Laplace equation (eq. 3), which states that capillary pressure is inversely proportional to the radius of curvature of the meniscus.

$$u_w - u_a = - \frac{4T \cos \theta}{d} \quad (3)$$

Where T is the surface tension and d is the pore diameter. Consequently, in larger pores, the radius r is greater, and the capillary pressure required to desaturate them is lower. This means that larger pores will tend to desaturate at low suction values compared to smaller pores, leading to a rapid soil desaturation. Similarly, poorly graded soils with similarly sized grains will have

a narrower range of pore sizes, which results in a faster and less gradual desaturation compared to well-graded soils.

3.3.1.1 Theoretical background: hydrological behaviour

The relationship between the amount of water present in the soil (e.g., water void ratio e_w , degree of saturation S_r , volumetric water content θ_w) and suction ($u_a - u_w$) is defined as the *soil water retention curve* (Figure 3.23). This relationship describes the hydrological behaviour of an unsaturated soil and therefore its capacity to store water, which varies with the soil's granulometric characteristics, expressed in terms of grain size and gradation.

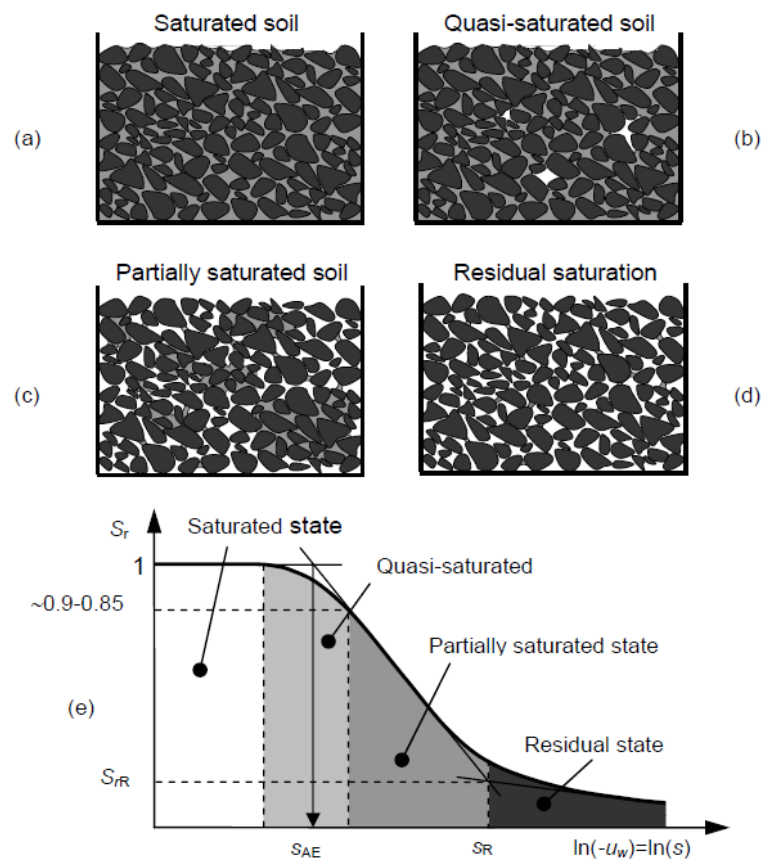


Figure 3.23 - Soil water retention curve and phases of saturation (from Tarantino, 2010).

The water retention curve is typically represented by plotting suction values on a logarithmic scale on the x-axis and the volumetric water content or degree of saturation on the y-axis. Regardless of the granular characteristics of the porous medium, the water retention curve will always exhibit four main phases:

Saturated phase: all pores are completely filled with water, the degree of saturation is $S_r = 1$, and consequently, the suction is close to zero.

Quasi-saturated phase: as suction increases, the air entry value (S_{AE}) is reached. Beyond this value, air begins to penetrate the largest pores, but the majority of the soil remains saturated. The degree of saturation starts to decrease slightly, although remaining at high values ($S_r \approx 0.85-0.9$).

Partially saturated phase: it corresponds to the steepest section of the curve, which is characterised by a rapid soil desaturation. Small variations in suction cause a significant decrease in the volumetric water content.

Residual phase: almost all capillary water has been removed. The remaining water is found mainly in the form of isolated menisci or thin films adhering to the surface of the solid particles. Despite reaching high suctions, it is very difficult to remove this residual water content. For this reason, the degree of saturation remains constant at a minimum value, defined as the residual degree of saturation (S_{rR}). The residual degree of saturation represents the minimum amount of water that can be present in the soil.

The relationship between the degree of saturation (S_r) and suction (ψ) is hysteretic. The water retention curve describes the soil behaviour during both the drying phase, when the soil state goes from $S_r=1$ to $S_r=S_{rR}$, and the wetting phase, when the soil starts from a dry state and tends towards saturation. When a dry soil is wetted, the water cannot displace all the air present in the pores, thus leading to the formation of trapped air bubbles. This trapped air reduces the total volume available for water, which means that for a given suction, the water content is lower than what it would be if the soil was drying. Consequently, the water retention behaviour of a soil drying from a saturated state (the "main drying curve") is different from the behaviour of a soil being wetted from a dry state (the "main wetting curve"), enabling the identification of two curves: the main drying and main wetting curves. Between the main drying and main wetting curves, there are intermediate curves called scanning curves, which describe the water retention behaviour of a soil undergoing incomplete wetting and drying cycles. Unlike the main drying and wetting curves, which start from a fully saturated state and a completely dry state respectively, scanning curves represent the intermediate paths within the hysteresis loop (Figure 3.24).

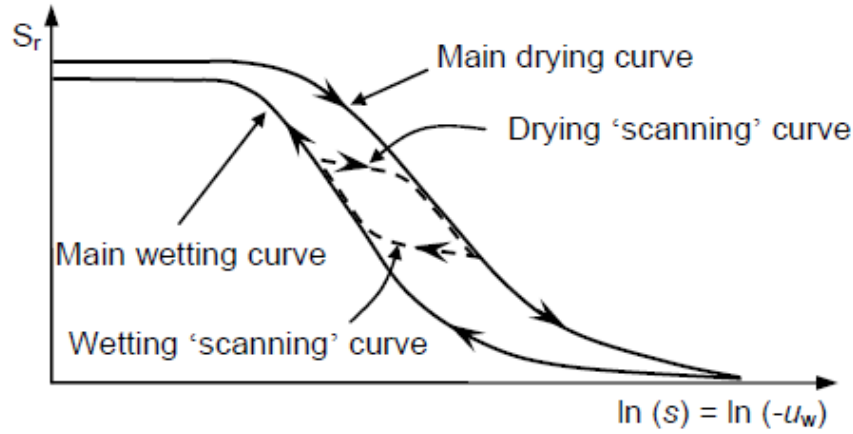


Figure 3.24 - Hysteresis of water retention behaviour in soils (from Tarantino, 2010).

The complex relationship between suction and the degree of saturation (i.e., hysteretic behaviour) has a direct and significant impact on the hydrological behaviour of soil, particularly on its ability to transmit water.

In a saturated soil, water occupies all the pores, and flow occurs relatively freely through the interconnected channels. In this state, the saturated permeability (k_{sat}) is at its maximum and is constant, representing an intrinsic soil parameter determined by its particle size distribution and pore geometry.

As the soil desaturates, the presence of air within the pores hinders the passage of water, making the water's flow path more complex. Consequently, the effective permeability k decreases drastically as the degree of saturation falls. The effective permeability (k) represents the instantaneous permeability of the unsaturated soil and reflects the reduced capacity for water transmission due to the presence of the gaseous phase. By definition, it is always less than the saturated permeability (k_{sat}); that is, $k < k_{sat}$. Therefore, the dynamics of water flow under unsaturated conditions are no longer governed by k_{sat} , but by a dynamic parameter, the relative permeability (k_r) which expresses the ratio of the effective permeability to the saturated permeability.

$$k_r = \frac{k}{k_{sat}} \quad (4)$$

This parameter, which varies between 0 (completely dry soil) and 1 (saturated soil), is directly dependent on the degree of saturation (or suction), with a strongly non-linear relationship.

To accurately model this behaviour, the scientific literature has proposed various mathematical formulations that link the degree of saturation and relative permeability to suction. These formulations, such as the one by van Genuchten (1980), are crucial for predicting water

movement in unsaturated soils. The van Genuchten formulation is widely used because of it effectively describes the water retention curve and, through a set of empirical parameters, it allows for the calculation of relative permeability as a continuous function of the degree of saturation.

This model is known for its ability to adapt to a wide variety of soils and for its analytical form, which makes it very useful for numerical calculations in solving the Richards' equation (Richards, 1931) (Richards' equation is a partial differential equation that describes the movement of water in an unsaturated porous medium, such as soil).

The model provides a mathematical equation that continuously describes the main water retention curve (typically the drying curve) across the entire range of suctions by relating the water content (θ) to the matric potential (ψ) through a series of parameters (eq. 5):

$$\vartheta = \vartheta_r + \frac{\vartheta_s - \vartheta_r}{(1 + |\alpha\psi|^n)^m} \quad (5)$$

The equation contains four independent parameters (ϑ_s , ϑ_r , α , and n), which must be estimated from observed soil water retention data. Specifically, ϑ_s represents the volumetric water content at saturation; ϑ_r is the residual volumetric water content; α is a parameter related to the air entry pressure (S_{AE}), which is the minimum suction required for air to begin penetrating the largest pores in the soil, breaking the continuity of the water. The parameter α is the inverse of this pressure ($1/S_{AE}$). The parameter n is a dimensionless parameter that describes the slope of the water retention curve and has a direct relationship with the pore size distribution of the soil. Finally, m is related to n by the relationship $m=1-1/n$ and ψ represents the matric potential of the soil. Knowing the relationship that links volumetric water content to the degree of saturation (i.e., $S_r = \theta_w / N$, where N is the porosity), the formula can also be expressed in terms of the degree of saturation (eq. 6):

$$S_r = S_{r,res} + \frac{1 - S_{r,res}}{(1 + |\alpha\psi|^n)^m} \quad (6)$$

$S_{r,res}$ represents the residual degree of saturation. Consequently, as previously discussed, permeability is generally expressed as a combination of saturated permeability (k_{sat}) and relative permeability (k_r), which depends on the effective degree of saturation ($S_{r,e}$) as follows (eq. 7):

$$k = k_{sat} k_r(S_{r,e}) \quad (7)$$

In the formulation for relative permeability, the effective degree of saturation ($S_{r,e}$) instead of total degree of saturation (S_r) is considered. This methodological choice is based on the functional distinction between mobile and immobile water within an unsaturated soil matrix.

The residual degree of saturation ($S_{r,res}$), in fact, represents the portion of water that remains trapped in the soil even under high suction conditions. This water, held by capillarity in the smallest and most isolated pores or as a thin film on the surface of particles, is considered immobile and does not contribute significantly to water flow. Its presence, while increasing the total degree of saturation, does not affect the soil's capacity to conduct water. In contrast, the effective degree of saturation ($S_{r,e}$) is a normalised measure that considers exclusively the portion of the fluid that can move through the interconnected pores of the soil (eq. 8):

$$S_{r,e} = \frac{S_r - S_{r,res}}{1 - S_{r,res}} \quad (8)$$

Its formulation, in fact, eliminates the effect of residual water, allowing for a more accurate description of the variation in permeability (Figure 3.32).

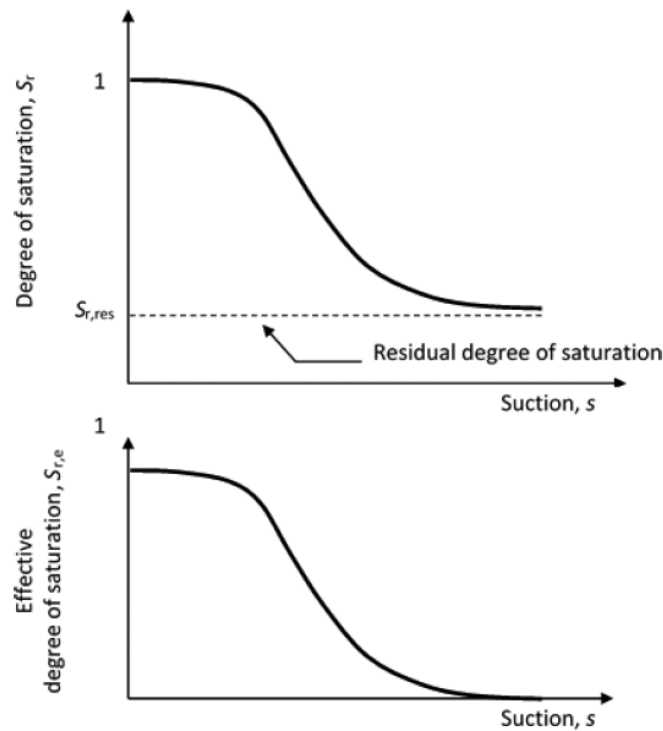


Figure 3.25 - Effective and residual degree of saturation (from Tarantino et al., 2019).

The experimental determination of permeability in an unsaturated regime is a very complex task. To overcome this difficulty, the scientific literature has introduced various semi-empirical relationships that allow for the derivation of relative permeability from the water retention curve. Among these formulations, the one proposed by van Genuchten (1980) is one of the most widely used and validated (eq. 9):

$$k_r = \sqrt{S_{r,e}} [1 - (1 - S_{r,e}^{\frac{1}{m}})^m]^2 \quad (9)$$

According to this formulation, relative permeability does not have a linear relationship with soil saturation, but its variation depends on the soil's textural and structural characteristics, which are expressed and quantified by the parameters of the van Genuchten curve (eq. 5). Therefore, the parameters of the van Genuchten model are not simple coefficients since they describe the geometry of the soil's pore network.

Unimodal water retention models, such as van Genuchten's, are effective at representing soils with a relatively homogeneous pore size distribution. However, these models fail to accurately capture the hydrological behaviour of more complex soils, which are characterized by a dual porosity, which is typical of many natural soils, dividing the pore space into two distinct but interacting systems: micropores and macropores. The presence of this dual structure can be due to natural phenomena such as fissures, root channels (i.e., biopores), or the formation of aggregates, as summarized as follows:

- Micropores: located within soil aggregates or between fine particles, are primarily responsible for water retention at high suctions. Due to their small size, they hold water with significant capillary force.
- Macropores: include fissures, root channels, and other preferential pathways, are fundamental for preferential water flow at low suctions. Their larger size allows for rapid drainage and water movement under near-saturated conditions.

This dual pore system significantly influences water movement in unsaturated soil, resulting in a water retention curve with a characteristic shape (Figure 3.26). The curve, in fact, shows a rapid decrease in water content at low suctions (corresponding to the emptying of macropores), followed by a more gradual slope at higher suctions, when water is drained from the micropores.

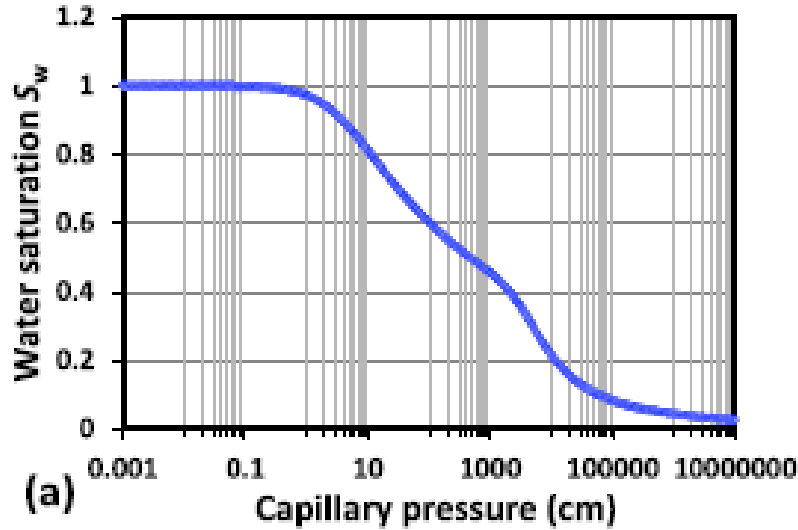


Figure 3.26 - Representative water retention curve for a dual-porosity soil (from Ghanbarian, 2021).

Unlike unimodal models (such as van Genuchten's), which assume a single pore distribution, bimodal models, like the one proposed by Durner (1994), describe the hydraulic properties of soil by considering its dual-porosity structure.

In Durner's model, later revisited by Zhang et al. (2022), the pore space is conceptualised as the superposition of two or more van Genuchten functions, each weighted by a factor w_i . This factor w_i represents the fraction of the total porosity associated with each pore system (e.g., w_1 for macropores and w_2 for micropores) (eq. 10). The sum of these factors must equal to one ($\sum w_i = 1$).

Consequently, the effective soil saturation is described as a weighted sum of the effective saturations of the individual pore systems (Zhang et al., 2022). This approach allows for a more realistic modelling of the water retention curve for complex soils, capturing both the rapid emptying of macropores at low suctions and the more gradual drainage of micropores at higher suctions.

$$S_{re} = w_1 \left[\frac{1}{1 + (\alpha_1 \psi)^{n_1}} \right]^{m_1} + w_2 \left[\frac{1}{1 + (\alpha_2 \psi)^{n_2}} \right]^{m_2} \quad (10)$$

In the context of dual-porosity soils, relative permeability is not described by a single function, as it is in unimodal models, but is intrinsically linked to the interaction between the two pore systems.

When the soil begins to dry, the macropores, characterised by larger diameters, empty rapidly. This desaturation drastically reduces the connectivity of this system, causing a significant

decrease in overall permeability. At this stage, water flow primarily occurs within the micropore matrix, which remains saturated for longer.

To describe this phenomenon, an approach analogous to Durner's model for the water retention curve is adopted. The overall relative permeability is calculated as a weighted sum of the relative permeabilities of the individual pore systems.

Consequently, unsaturated permeability can be expressed as the product of the saturated permeability and the total relative permeability (eq. 11):

$$k = k_{sat} * k_r \quad (11)$$

The total relative permeability is, in turn, a function of the hydraulic parameters of the individual pore systems and their relative weighting within the total soil porosity as follows (eq. 12):

$$k = k_{sat} \sqrt{S_{re}} \left\{ \frac{w_1 \alpha_1 \left[1 - \left(1 - S_{re}^{\frac{1}{m_1}} \right) \right] + w_2 \alpha_2 \left[1 - \left(1 - S_{re}^{\frac{1}{m_2}} \right) \right]}{w_1 \alpha_1 + w_2 \alpha_2} \right\}^2 \quad (12)$$

This approach allows for a more accurate representation of the retention curve and relative permeability in soils with complex structures, improving the prediction of water movement and solute transport.

3.3.1.2 Theoretical background: mechanical behaviour

In unsaturated soils, the presence of a negative pore pressure, or suction, plays a crucial role that extends beyond its simple hydrological component. This condition imparts an apparent cohesion to the soil, significantly influencing its mechanical behaviour. Conversely, in saturated soils, where suction is absent, shear strength depends exclusively on the friction between particles and effective cohesion, as expressed by the classic Mohr-Coulomb formula (see eq.1).

In unsaturated soils, however, the negative pore pressure alters the shear strength compared to that observed under saturated conditions. To account for this phenomenon, the classic Mohr-Coulomb formulation is extended by incorporating two additional parameters that describe the stresses to which the soil is subjected:

- the **net total stress** ($\sigma - u_a$), where σ is the applied total stress and u_a is the pore-air pressure.
- the **matric suction** ($u_a - u_w$), which represents the difference between the pore-air pressure (u_a) and the pore-water pressure (u_w).

The extended Mohr-Coulomb formula proposed by Fredlund and Morgenstern (1977) describes the shear strength of unsaturated soils by including these additional parameters (eq. 13):

$$\tau = c' + (\sigma - u_a) \tan (\phi') + (u_a - u_w) \tan (\phi_b) \quad (13)$$

where c' and ϕ' are the effective cohesion and friction angle, respectively, while ϕ_b is the additional friction angle that describes the increase in strength due to matric suction. This extended approach allows for a more accurate modelling of the shear strength of unsaturated soils, recognising the importance of suction as a stabilising factor.

The different shear strengths of soils under saturated and unsaturated conditions, are graphically represented through a three-dimensional extension of the classic Mohr-Coulomb diagram (Figure 3.27). The horizontal axis ($\sigma_v - u_a$) represents the net total stress, which is an extension of the effective stress used for saturated soils. The vertical axis shows the shear stress, while the z-axis shows the matric suction ($u_a - u_w$).

Moving from circle 3 to circle 1 (in a Mohr diagram context), there is a decrease in pore-water pressure (u_w). This pressure transition from positive values ($u_w > 0$), indicative of a saturated state, to negative values ($u_w < 0$), which mark an unsaturated state by introducing matric suction ($u_a - u_w$). Basically, for a constant net total stress, this suction imparts greater apparent cohesion (c') to the soil.

This resulting increase in cohesion involves an upward and rightward shift of the Mohr-Coulomb failure. Consequently, the Mohr circles representing failure conditions shift progressively towards higher normal stress values, thus ultimately leading to a significant increase in the mechanical soil strength.

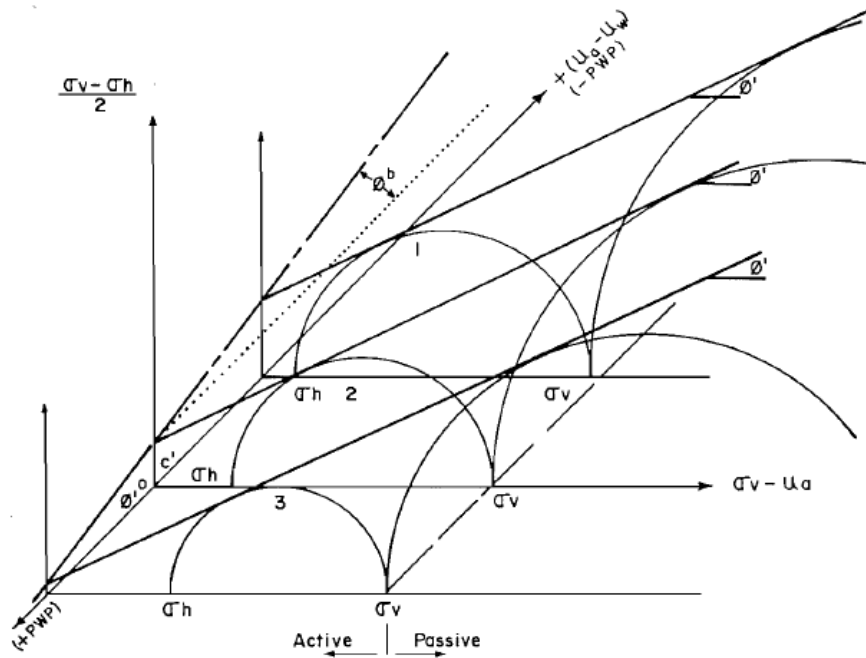


Figure 3.27 - The Mohr circle diagram shows the transition in failure conditions from saturated to unsaturated soil (from Pufahl et al., 1983).

Moreover, the transition from saturated to unsaturated soil conditions implies a variation of the horizontal stress, which is crucial, as horizontal stress is directly correlated to the Rankine's active stress (Rankine, 1857).

This means that the soil's degree of saturation not only influences shear strength, but also directly affects the active stress exerted on a structure. This aspect is fundamental for the stability of retaining structures, such as dry-stone walls, as it defines the forces to which the structure is subjected.

3.3.1.3 Rankine theory of active earth pressure

Rankine's theory is a fundamental geotechnical model that calculates the lateral pressures a soil exerts on a retaining structure. The main objective is to determine the "earth pressure" or the resultant force acting on a wall under limit equilibrium conditions. The theory analyses three distinct equilibrium states relative to the ratio between horizontal (σ_h) and vertical (σ_v) stresses: at-rest ($\sigma_h = \sigma_v$), passive ($\sigma_h < \sigma_v$), and active ($\sigma_h > \sigma_v$). The latter is particularly important in the context being analysed.

Active earth pressure represents the condition of minimum lateral stress that a soil can exert on a retaining structure, whose development involves soil deformation and the mobilisation of its shear strength. This process begins from an at-rest state (K_0), where the effective vertical (σ_{v0}')

and horizontal (σ_{h0}') stresses are in geostatic equilibrium, and the soil is stable, with stresses below its shear strength.

The transition from the at-rest condition (K_0) to the active stress condition (K_a) is induced by a gradual movement of the retaining wall *away* from the backfill (Figure 3.35). Even a relatively small displacement can trigger a horizontal strain within the soil. In this scenario, σ_{v0}' remains essentially constant, while the σ_{h0}' progressively reduces until it reaches the minimum value compatible with the mobilised soil shear strength, thus defining the active limit equilibrium condition.

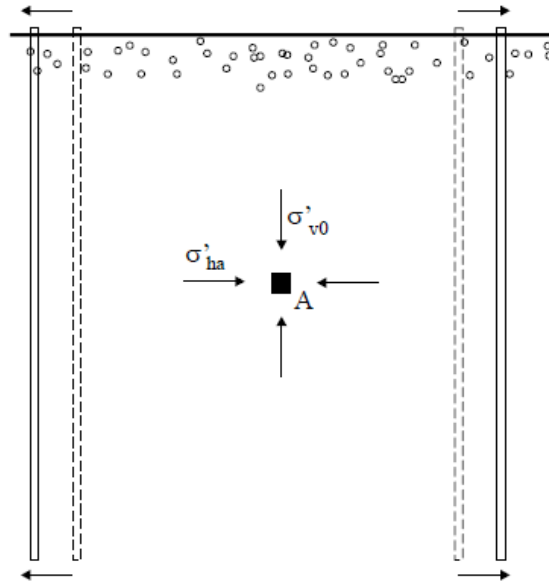


Figure 3.28 - Active earth pressure (Facciorusso et al., 2006).

The Rankine's active earth pressure coefficient (K_A) for a cohesionless soil (cohesion $c'=0$) with a backfill surface inclined at an angle α to the horizontal is expressed by the following relationship (eq. 14):

$$K_A = \left(\frac{\cos \alpha - \sqrt{\cos^2 \alpha - \cos^2 \phi'}}{\cos \alpha + \sqrt{\cos^2 \alpha - \cos^2 \phi'}} \right) \quad (14)$$

The effective horizontal active pressure (σ_{ha}') at a given depth Z , in a soil mass with unit weight γ is given by (eq. 15):

$$\sigma_{ha}' = K_A \sigma_{v0}' = K_A \gamma Z \quad (15)$$

The total active thrust (S_A) acting on the wall, for a wall height H , is obtained by integrating the linear distribution of the effective active horizontal stress along the height:

$$S_A = \frac{1}{2} \gamma H^2 K_A \quad (16)$$

In the case of unsaturated soils, the calculation of active earth pressure is achieved by extending and combining the principles of the Rankine's theory with the modified Mohr-Coulomb criterion to include the effect of matric suction.

Consequently, the formula for (σ'_{ha}) in an unsaturated soil includes terms that reflect the influence of both suction and cohesion. At a given depth Z , the equation takes a form that considers both the thrust due to the soil's weight and the stabilising effect of cohesion and matric suction (eq. 17):

$$\sigma'_{ha} = (\gamma Z - u_a) K_A - 2 c' \sqrt{K_A} - (u_a - u_w) \tan \varphi_b \sqrt{K_A} \quad (17)$$

where the total active thrust (S_A) in an unsaturated soil is obtained by integrating the distribution of the active horizontal stress along the height of the wall. The presence of cohesion (both effective and apparent due to suction) significantly reduces the magnitude of the active stress acting on the structure (eq. 18):

$$S_A = \frac{1}{2} \gamma H^2 K_A - 2 c' \sqrt{K_A} H \quad (18)$$

This stabilising effect can become predominant, such as in conditions where cohesion and suction are sufficiently high, when the stabilising term can even exceed the thrust due to the soil's self-weight, leading to a theoretically negative active thrust for the lowest depths. In such a scenario, the soil "self-supports" for a certain critical height.

3.3.1.4 Role of evapotranspiration

As previously discussed, the hydrological and geomechanical properties of unsaturated soils are closely correlated with changes in suction, which directly influences shear strength and, consequently, the soil's active thrust. Understanding the mechanisms that cause desaturation is therefore of fundamental importance.

Evapotranspiration (ET) represents the sum of direct evaporation from the soil surface and plant transpiration. This dynamic and complex process is the primary mechanism by which water is removed from the soil profile, especially during periods without rainfall, and transferred to the atmosphere. The combined action of these two phenomena leads to a progressive decrease in volumetric water content and, consequently, an increase in suction.

Therefore, quantifying ET is essential for the hydro-mechanical modeling of unsaturated soil.

Potential evapotranspiration (PET) is defined as the maximum amount of water a soil can release to the atmosphere through surface evaporation and plant transpiration. This value cannot be measured directly but is estimated from meteorological data: i.e., net solar radiation, air temperature, air humidity and wind speed. PET is calculated by integrating these meteorological parameters within empirical and semi-empirical methods; among the most well-known is the Penman-Monteith method (Monteith, 1965).

The Penman-Monteith method is a physical-mathematical model widely recognized as the international standard (specified in FAO-56) (Allen, 1998) for calculating reference potential evapotranspiration (PET). It is based on a combination of an energy balance and an aerodynamic balance to estimate the amount of water that a hypothetical standard surface releases into the atmosphere, whose meaning is described below:

Energy Balance: based on the principle of energy conservation, the energy available for evapotranspiration (PET) is given by the net radiation (R_n), which is the difference between incoming and outgoing solar energy (albedo, α), minus the ground heat flux (G). This energy is primarily used for converting water from a liquid to a gaseous state (latent heat, λE) and for heating the air (sensible heat, H) (eq. 19):

$$PET_{Rn} = \frac{1}{\lambda} \left(\frac{\Delta R_n}{\Delta + \gamma \left(\frac{r_a + r_c}{r_a} \right)} \right) \quad (19)$$

Aerodynamic Balance: it describes the movement of water vapor from the air just above the vegetation surface to the atmosphere. The vapor flux depends on the vapour pressure deficit (i.e., the difference between the saturated vapour pressure inside the leaves and the actual vapour pressure of the air) and the resistance to vapor transfer (eq. 20):

$$PET_{VPD} = \frac{1}{\lambda} \left(\frac{\rho_a c_{pa} \rho_{v0} \left(1 - \frac{RH}{r_a} \right)}{\Delta + \gamma \left(\frac{r_a + r_c}{r_a} \right)} \right) \quad (20)$$

Therefore, the combination of these two terms allows for the calculation of PET as follows (eq. 21):

$$PET = \frac{1}{\lambda} \left(\frac{\Delta R_n + \rho_a c_{pa} \rho_{v0} \left(1 - \frac{RH}{r_a}\right)}{\Delta + \gamma \left(\frac{r_a + r_c}{r_a}\right)} \right) \quad (21)$$

where R_n represents the net radiation, Δ is the slope of the saturated vapour pressure curve as a function of temperature, ρ_a is the density of the air, C_{pa} is the specific heat of the air, ρ_{v0} is the saturated vapour density, γ is the psychrometric constant, and r_a and r_c are the aerodynamic resistance and vegetation resistance, respectively.

Aerodynamic resistance and vegetation resistance are two very important parameters during the evapotranspiration process, as they refer to the soil cover characteristics and how these can influence the evapotranspiration process, as summarized below:

- **Aerodynamic resistance (r_a)** is a pivotal parameter that governs the transfer of water vapour and heat between an evaporating surface and the atmosphere. It functions as a barrier to this transfer, directly influencing evapotranspiration. Evaporation is driven by a vapour pressure gradient: water molecules leave the surface and tend to saturate the adjacent air layer (the boundary layer), which retards the process. For evaporation to continue, the vapour must be removed from the boundary layer into the atmosphere, a process primarily achieved by atmospheric turbulence. This parameter depends mainly on two factors:
 - Wind speed: higher wind speed increases turbulence, which reduces aerodynamic resistance. Consequently, a higher wind speed maintains a steep vapour pressure gradient between the surface and the surrounding air, facilitating faster evaporation and efficient heat transfer.
 - Surface roughness (z_{0m}): the roughness of a surface increases the turbulence of airflow. Roughness is directly related to the height and geometry of the vegetation (Figure 3.36). Consequently, as you move from bare soil to tall vegetation, the surface roughness and turbulence increase, leading to a progressive decrease in r_a .

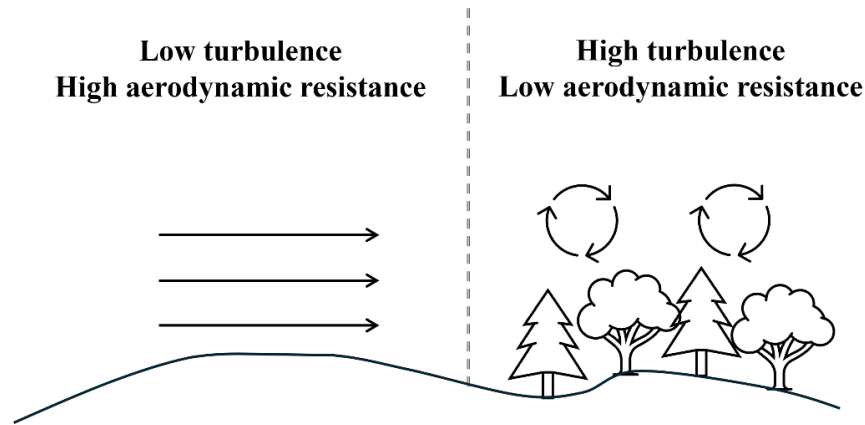


Figure 3.29 - Aerodynamic resistance in relation to the different characteristics of the soil surface and the presence of vegetation.

- **Vegetation resistance (r_c)** is a key factor in the evapotranspiration process that controls the rate at which water moves from the plant to the atmosphere. This resistance is essentially a measure of how difficult water vapour goes out through the stomata on the leaves (Figure 3.30). Vegetation resistance is correlated with the resistance of a single leaf (defined as stomatal resistance, r_s), which in turn depends on the leaf water potential (Ψ_{leaf}).

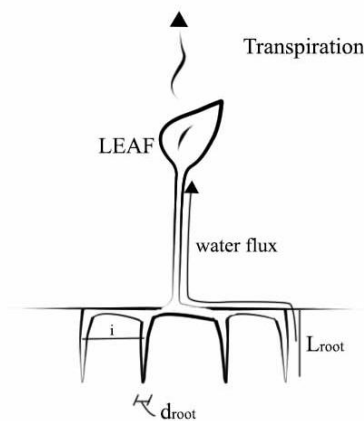


Figure 3.30 - Soil-Plant-Atmosphere Continuum (SPAC) model scheme (from Tarantino, 2016).

The Soil-Plant-Atmosphere Continuum (SPAC) regulates evapotranspiration through the movement of water, which is driven by a decreasing water potential (Ψ) gradient extending from the soil (Ψ highest) to the atmosphere (Ψ lowest). Under conditions of ample water availability, and provided that the leaf water potential (Ψ_{leaf}) remains above a critical threshold (Ψ_c), the stomatal resistance (r_s) is maintained at its minimum value (r_{sm}), and the ET rate is classified as potential. (Figure 3.31).

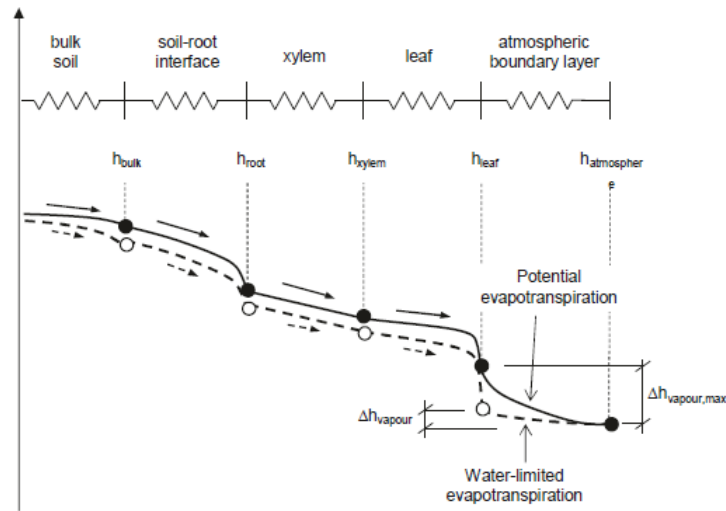


Figure 3.31 - Resistances in the Soil-Plant-Atmosphere Continuum (SPAC) (from Tarantino et al., 2023).

When evaporative demand exceeds the water supply capacity of the soil-root system, a decrease in leaf water potential (Ψ_{leaf}) occurs until a critical threshold (Ψ_c) is reached. This condition triggers stomatal closure, which constitutes the fundamental mechanism regulating the transition from potential to actual evapotranspiration (AET). The resulting significant increase in stomatal resistance (r_s) causes ET to become a process limited by water availability (Federer, 1975). At this stage, the evapotranspiration rate is intrinsically controlled by the capacity of the soil-plant hydraulic system to release water, becoming independent of atmospheric demand (Figure 3.32). The maximum evapotranspiration limit (ET_{lim}) is reached when the soil water suction becomes so high that it is considered asymptotically "infinite".

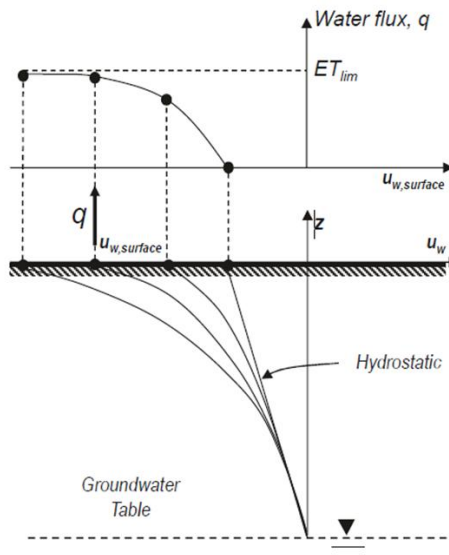


Figure 3.32 - Maximum soil-limited water transfer to the atmosphere (from Tarantino et al., 2023).

In line with this, two distinct regimes can be identified based on water availability, which differentiate PET from water-limited evapotranspiration (Figure 3.33):

- **Energy-limited regime:** when PET is less than the maximum water flux (ET_{lim}) that the soil can transfer, and $AET = PET$. The limiting factor is not water availability but the energy available for evaporation.
- **Water-limited regime:** when PET is greater than ET_{lim} , and AET is limited by water availability and will equal the maximum transferable flux (i.e., $AET = ET_{lim}$).

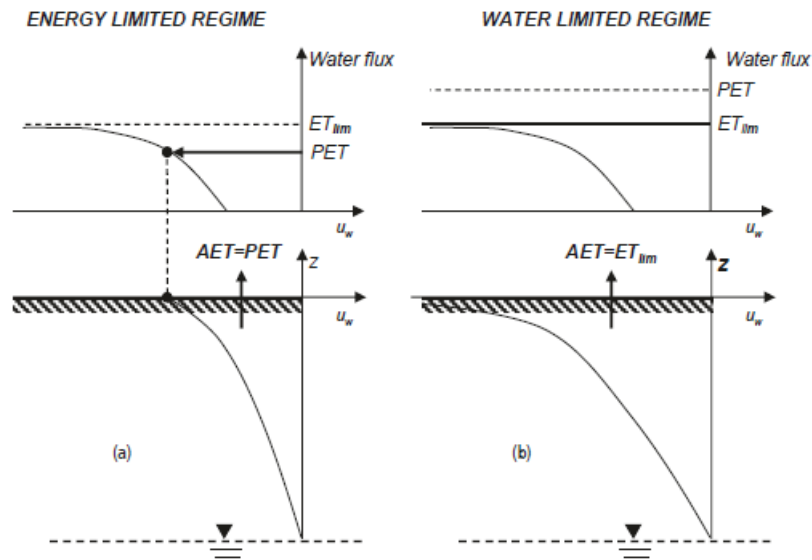


Figure 3.33 - Water and energy limited regimes (from Tarantino et al., 2023).

In the water-limited evapotranspiration regime, a correction factor (β) is applied to PET to calculate AET. This factor, which ranges from 0 to 1, describing how PET is reduced due to water stress (eq. 22):

$$AET = PET \beta \quad (22)$$

The model by Feddes et al. (1978) assumes that this factor is a function of the soil suction (or matric potential) in the root zone. The main idea is that water uptake by the roots is not constant but depends on the soil water pressure.

The model identifies four critical points on the suction curve that influence water availability for the plant (Figure 3.34).

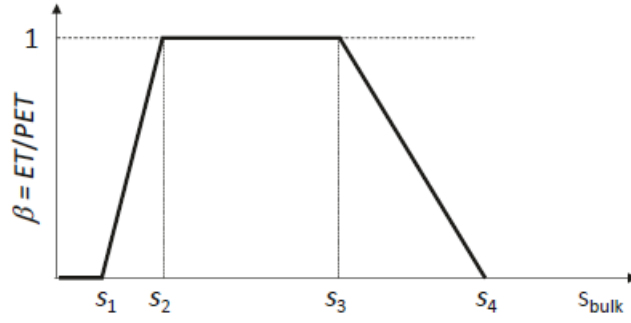


Figure 3.34 - Feddes reduction function (from Tarantino et al., 2023).

When the soil is completely saturated (S_1) or completely dry (S_2), the plant is unable to absorb/extract water. Consequently, ET is considered to be zero. Between the wilting point (S_2) and the critical threshold (S_3), transpiration is at its maximum and is not limited by water availability. Under these conditions, $\beta=1$ and AET equals PET (AET=PET). The point S_3 corresponds to the soil suction above which plant transpiration begins to be limited. The threshold suction S_3 marks the transition from energy-limited (potential) to water-limited evapotranspiration.

The factor β is not a fixed value but varies as a function of the soil's suction (Ψ). The formula used to calculate the correction factor, in the case where the soil water potential is more negative than the permanent wilting point, is (eq. 23):

$$\beta = \frac{T}{PT} = \frac{\Psi_{bulk}^{1-\lambda} - (\Psi_{leaf})^{1-\lambda}}{(\Psi_3)^{1-\lambda} - (\Psi_{leaf})^{1-\lambda}} \quad (23)$$

where:

Ψ_{bulk} : soil water potential (in the root zone).

Ψ_{leaf} : water potential in the root xylem.

Ψ_3 : critical threshold of soil water potential beyond which a plant is no longer able to extract water from the soil.

λ : empirical parameter whose value depends on the plant's hydraulic properties. Its value influences how quickly the transpiration rate decreases as the soil dries out.

3.3.2 Hydrological model development: methodological approach

This methodological approach has enabled the quantification and comparison of the soil's capacity to store and transfer water in order to investigate the impact of different land covers on the local hydrological cycle. The creation of a representative hydrological model requires a

comprehensive understanding of the intrinsic soil parameters and the external forcings that influence water dynamics.

Intrinsic Soil Hydraulic Properties

These properties depend on the soil's physical and mechanical characteristics, such as particle size distribution, porosity, and bulk density, describing how soil responds to variations in moisture conditions: **water retention curve (WRC)**, **saturated permeability (k_{sat})**, **relative permeability (k_{rel})**.

Intrinsic soil hydraulic properties: water retention curve (WRC)

The Water Retention Curve (WRC) is the relationship describing how the volumetric water content of the soil changes as a function of the matric potential and is fundamental to understanding the hydraulic behaviour of unsaturated soil. To analytically model this relationship, the van Genuchten model, extensively discussed previously (as illustrated in paragraph 3.3.1.1), was adopted for this study. Specifically, the Van Genuchten model transforms discrete field measurements into a continuous function (i.e., WRC), providing a mathematically tractable representation of soil hydrological processes. The parameters of the model in this research were calibrated using a heuristic and iterative process, grounded in experience and graphical analysis, in the absence of an automated numerical algorithm. The primary objective was the visual minimisation of the discrepancy between the theoretical curve and the experimental data related to the suction-water content relationship. The real-time manual variation of the parameters allowed for the identification of the best fit and ensured greater physical interpretability of these parameters, enabling the assessment of the impact of each modification on the morphology of the Water Retention Curve (WRC). The parameters obtained from the WRC that best approximate the experimental data form the basis for characterising the suction-water content relationship and for the derivation of crucial hydraulic properties for hydrological modelling, such as saturated permeability (k_{sat}) and relative permeability (k_{rel}).

Intrinsic soil hydraulic properties: saturated permeability (k_{sat})

Saturated permeability (k_{sat}) is a fundamental parameter that describes the capacity of a soil to allow water to flow through it when all its pores are completely filled. It is important to note that in unsaturated soils, permeability is not constant but decreases drastically as the water content decreases.

In order to define the relative permeability, it is essential to know the value of the saturated permeability (k_{sat}). Various empirical models have been developed in the literature that allow to estimate k_{sat} from the water retention curve parameters. Specifically, two widely used models for estimating saturated permeability from the van Genuchten (VG-WRF) model parameters have been considered.

Model by Guarracino (2007)

This model estimates saturated permeability (k_{sat}) using the α parameter from the van Genuchten water retention curve. It assumes that soil pores can be treated as parallel capillary tubes with a fractal distribution, thereby establishing a quadratic relationship between $k_{sat,G}$ and α reported as follows (eq. 24):

$$k_{sat,G} = 1.74 * 10^5 \frac{2-D}{4-D} \vartheta_s \alpha^2 \quad [k_{sat}] = \frac{cm}{h} \quad (24)$$

where D is the fractal dimension, which Guarracino set to a specific value (1.996), and α and ϑ_s are two parameters of the van Genuchten curve. They represent the suction value at which the soil begins to desaturate and the porosity or saturated volumetric water content, respectively.

Model by Mishra and Parker (1990)

This is a widely recognised empirical formulation for estimating saturated permeability ($k_{sat,MP}$) from the parameters of the van Genuchten water retention function (VG-WRF) (eq.25):

$$k_{sat,MP} = \frac{3,89-10^5}{T_{MP}} \vartheta_s^{\frac{5}{2}} \alpha^2 \quad [k_{sat}] = \frac{cm}{h} \quad (25)$$

where T_{MP} is a tortuosity factor which accounts for the complexity of the path that water follows through the soil pores. The original value proposed by Corey (1979) is 2.5. Like the Guarracino model, the Mishra and Parker formulation is also based on two key parameters of the van Genuchten curve, namely ϑ_s and α .

Relative permeability (k_{rel})

Once the k_{sat} value was established, the relative permeability curves were derived to evaluate the variation in water flow as soil saturation conditions change. To conduct a sensitivity analysis of the soil hydrological model, the estimation of unsaturated permeability was undertaken using

both the van Genuchten-Mualem model (3.3.1.1 hydrological behaviour) and the empirical Kozeny-Carman model. The latter, which is widely used in scientific literature, was also considered to describe the relationship between unsaturated permeability and saturation.

Kozeny-Carman (1927): it consists of a semi-empirical relationship originally developed to estimate the saturated permeability (k_{sat}) of porous media (eq. 26).

$$k_{sat} = \left[\frac{g}{2\eta} \frac{1}{S_0^2} \frac{e^3}{1+e} \right] \quad (26)$$

However, its extension has been used as a basis for the development of more complex models to describe water flow under unsaturated conditions by considering permeability as a function of soil saturation. Therefore, relative permeability (k_{rel}) is defined as the ratio of unsaturated to saturated permeability, as a function of effective saturation ($S_{r,e}$) (Paragraph 3.3.1.1) (eq. 27).

$$k_{rel} = \left[\frac{g}{2\eta} \frac{1}{S_0^2} \frac{e^3}{1+e} \right] * S_{r,e}^3 = k_{sat} S_{r,e}^3 \quad (27)$$

The exponent of $S_{r,e}$ in the eq. 30 can vary based on the soil's properties and the specific model. Higher exponent values indicate a greater sensitivity of unsaturated permeability to a decrease in the degree of saturation.

The van Genuchten model is considered as the most representative for describing WRC and the saturated-unsaturated transition, providing a more faithful (and thus less conservative) and reliable description. Conversely, the Kozeny-Carman model is the least representative due to its inadequacy in accurately capturing the complexity of unsaturated flow processes. This formulation typically underestimates the unsaturated permeability, resulting in a more conservative prediction.

External Hydrological Forcings

External hydrological factors, such as precipitation and evapotranspiration, act as the boundary conditions of the system, driving variations in the soil water balance: **precipitation, evapotranspiration (ET).**

Precipitation conditions were determined using data recorded by the rain gauge installed at the meteorological station within the study area. Conversely, the Potential Evapotranspiration (PET) rate was calculated using the Penman-Monteith method (Section 3.3.1.4). In this model, three fundamental parameters allow for the discrimination of the different vegetative conditions across the three study sites, irrespective of climatic variables: α , the surface albedo; z_0 , the surface roughness and r_c , the canopy resistance.

Albedo (α) is a dimensionless parameter that indicates the fraction of shortwave solar radiation reflected by a surface and it directly influences the evapotranspiration rate through net radiation (R_n) eq. (28).

$$R_n = (1 - \alpha)S_r \quad (28)$$

Albedo values are within the interval [0,1]: a value of 0 indicates complete absorption of the radiation, while 1 indicates total reflection. The value of albedo is not constant as it depends on the physical characteristics of the surface. It varies according to the nature of the soil (e.g., bare or vegetated), the type of vegetation cover, and the phenological state of the vegetation, that is, its developmental stage which in turn affects its reflective capacity. In the present study, the albedo value was estimated based on empirical studies that correlate soil conditions (such as surface type and vegetation cover) with their reflective properties (Table 3.3).

Table 3.3 - Indicative Albedo Values for Different Natural Surfaces (Brutsaert, 1982).

Surface	Albedo, α
Deep water	0.04-0.08
Dark wet soil; plowed field	0.05-0.15
Gray soil; bare soil	0.15-0.25
Dry soil; desert	0.20-0.35
White sand; lime	0.30-0.40
Green grass and low vegetation	0.15-0.25
Dry grass	0.15-0.20
Dry grassland and savannah	0.20-0.30
Coniferous forest	0.10-0.15
Deciduous forest	0.15-0.25
Forests with melting snow	0.20-0.30
Old, dirty snow cover	0.35-0.65
Clean, stable snow cover	0.60-0.75
Fresh dry snow cover	0.80-0.90

Surface roughness (z_0) and canopy resistance (r_c) were also derived from empirical studies and depend on specific surface and vegetation conditions as described below.

Surface roughness (z_0) is a parameter that quantifies the ruggedness of the soil surface. Despite not directly measurable, its value is estimated based on the height and density of the vegetation. This parameter is fundamental because it affects the aerodynamic resistance (r_a), which in turn regulates wind turbulence and the transfer of water vapour from the surface to the atmosphere (Section 3.3.1.4). To determine the value of surface roughness, the method proposed by Trombetti and Tagliazucca (1994) (Table 3.4) was used.

Table 3.4 - Values of the surface roughness length z_0 for different types of surfaces (after Trombetti and Tagliazucca 1994).

Surface	z_{0m} (m)
Flat desert	0.0005-0.005
Mown grass, few trees in winter time	0.006-0.01
Uncut grass, isolated trees, airport runway	0,02
Wheat stubble plain ($h_0=18$ cm)	0,025
Long grass, crops, farmland, rocky ground ($h_0=60$ cm)	0,05
Many hedges	0,08
Many trees	0.15-0.3
High vegetation ($h_0=1-2$ m)	0,2
Trees ($h_0=10-15$ m)	0.4-0.7
Forests	0.7-1.2

Canopy resistance depends on both vegetation and soil conditions. It represents the resistance offered by the vegetation canopy to the transfer of water vapour to the atmosphere. Values of (r_c) for different types of vegetation are provided in Table 3.5, according to Monteith (1965). The same table also reports values for surface roughness length (z_{0m}), aerodynamic resistance (r_a), and albedo (α). The r_c parameter is fundamental for distinguishing between potential and actual evapotranspiration, as it reflects the physiological response of the plant to environmental conditions.

Table 3.5 - Indicative values of canopy resistance for different types of vegetation, surface roughness (z_{0m}), aerodynamic resistance r_a and albedo α .

Surface	r_{cm} (sm^{-1})	z_{0m} (m)	r_a (sm^{-1})	α
Bare surface		0,001	170	0,35
Lawn	410	0,006	100	0,25
Rough pasture	50	0,02	63	0,2
Timothy	50	0,05	36	0,18
Pine forest	90	0,4	8	0,1
Eucalyptus forest	35	0,4	7	0,1

The thermodynamic properties of air parameters are also incorporated into the formula, which is a crucial element for precisely quantifying the influence of energy and temperature on the air capacity to absorb and retain water vapour. These parameters have been summarised in Table 3.6.

Table 3.6 - Definition of parameters for heat and mass balance.

T_0	T_0	ρ_v	L	R_w	c_{pw}	c_{pv}	c_{pd}	P
(°C)	(°K)	(Pa)	(J/kg)	(J/K kg)	(J/K kg)	(J/K kg)	(J/K kg)	(kg m ⁻³)
20	293,15	2337,3	2453000	461,9	4182	1846	1005	1,2

ρ_v denotes the maximum vapour pressure that water vapour can exert in the air at a given temperature while L is the latent heat of vaporisation, defined as the energy required to transform a unit mass of liquid water into water vapour. P is the local atmospheric pressure, which influences both the air density and the diffusion rate of water vapour, T_0 is the air temperature while R_w , c_{pw} , c_{pv} and c_{pd} are defined specific constants for energy and thermal balances: they include the specific gas constant for water vapour (R_w), the specific heat capacities of dry air (c_{pd}), water vapour (c_{pv}), and liquid water (c_{pw}).

The aforementioned parameters are necessary for discriminating potential evapotranspiration (PET) across different vegetation contexts. To subsequently determine actual evapotranspiration (AET), it is essential to know the Ψ_{leaf} and Ψ_3 parameters (see paragraph 3.3.1.4). In this research, the Ψ_{leaf} value was determined based on literature studies describing the suction conditions that a plant can tolerate (Rodriguez et al., 2022), considering the wetting and drying cycles and the specific plant type. These literature data were then used to identify representative values through a trial-and-error validation procedure.

The Ψ_3 parameter, conversely, was determined by the graphical analysis of the temporal relationship between cumulative potential evapotranspiration (ET_{cum}) and the net change in soil water content (ΔV_w). This biphasic relationship is crucial as it allows for the identification of the exact point where the atmospheric evapotranspiration demand begins to exceed the water available in the soil. This condition corresponds to a divergence in the trend of the cumulative ET_{cum} and ΔV_w curves (Wilson et al., 1997). This point of divergence signals the precise moment when soil water availability becomes the limiting factor for the evapotranspiration process, marking the transition from a PET to an AET regime. Consequently, the soil water content value recorded at this transition is correlated, via the Water Retention Curve, with a

well-defined suction value. This suction value represents the critical water potential Ψ_3 , which is indispensable for calculating the correction factor used in the estimation of actual evapotranspiration.

3.3.3 Numerical modelling of the hydrological response - GeoStudio SEEP/W

The primary aim of this study is to validate the hydrological model developed using monitoring data and to accurately reproduce the hydrogeological dynamics of the investigated sites. This will allow for the definition of distinct water circulation patterns and the influence of vegetative conditions on pore pressure variations.

To achieve this goal, the hydrological models were integrated into a hydrological modelling software to perform a seepage analysis. The numerical modelling was conducted using SEEP/W (GEO-SLOPE International Ltd., 2002), a finite element code. This software was selected due to its effectiveness in simulating groundwater flow under various conditions. A key feature of SEEP/W is, in fact, its ability to model the behaviour of unsaturated soils, accounting for matric suction. This enables an accurate study of the influence of external forcings on the intrinsic hydrological variation within the soil.

The software facilitates the simulation of transient flow conditions, thereby allowing for the modelling of temporal variations in water flow and pore-water pressures. This function is fundamental for investigating the soil response to dynamic events of flow entering or exiting the system. The behaviour of groundwater flow in SEEP/W is governed by a second-order, non-linear partial differential equation, also known as the continuity equation, which is derived from the combination of Darcy's Law, which describes the flow velocity through a porous medium as a function of the hydraulic gradient and permeability, with the principle of mass conservation for a representative elementary volume of soil. The general form of the partial differential equation for two-dimensional transient flow utilised in the GeoStudio SEEP/W module is as follows (eq. 29):

$$\frac{\delta}{\delta_x} \left(K_x \frac{\delta_h}{\delta_x} \right) + \frac{\delta}{\delta_y} \left(K_y \frac{\delta_h}{\delta_y} \right) = \frac{\delta \vartheta}{\delta t} \quad (29)$$

This equation represents the mathematical foundation for describing fluid flow through a porous medium, stating that the change in water mass within a control volume is equal to the net flow entering or leaving that volume. The left side of the equation describes the net volumetric flow into or out of an elementary volume, per unit of time. This term quantifies the spatial variation of the flow, which is determined by the permeability and the hydraulic head

gradient. Conversely, the expression on the right side quantifies the change in water storage within the elementary volume over time, namely the amount of water that the soil absorbs or releases, causing a change in its volumetric water content.

Within the equation, h represents the total energy of water in the soil and is the driving force of the flow, defined as the sum of the pressure head (h_p) and the elevation head (y). The parameters k_x and k_y indicate the permeability along the x and y directions, allowing for the modelling of anisotropic materials. Finally, the term ϑ describes the volume of water per unit of total soil volume, allowing for transient analyses. Basically, ϑ represents the change in water storage over time and varies as a function of the pore water pressure.

For transient flow modelling using the SEEP/W module, it is imperative to first establish the working domain and define the soil's intrinsic hydrological functions, particularly the Water Retention Curve and relative permeability. It is equally crucial to specify the external hydrological boundary conditions. The SEEP/W module can simulate both inflow and outflow, allowing for the representation of phenomena such as infiltration and/or evapotranspiration. In both cases, the software offers the option to apply corrective functions. This feature is particularly useful for evapotranspiration, as it allows for the modelling of the transition from potential to actual evapotranspiration using experimental data.

As SEEP/W is a finite element method-based software, the definition of a computational mesh is a fundamental step. This mesh consists of elements interconnected by nodes, within which the flow equation representative of the hydraulic problem under consideration is applied and solved. The mesh discretisation process is automatically managed by the software; however, the mesh can be refined by the user to increase the accuracy of the analysis in specific areas of interest. The detailed application of the aforementioned methodology to the specific case study will be addressed in Paragraph 5.3.

3.3.4 Limit equilibrium stability analysis - GeoStudio SLOPE/W

In the GeoStudio software, suite, the SEEP/W module has been seamlessly integrated with the SLOPE/W module in a multi-physics analysis.

This integration allows the pore-water pressure results derived from the SEEP/W hydraulic analysis to be used as fundamental input data for the slope stability simulation performed by SLOPE/W.

The primary objective of this combined analysis is to establish a clear and quantifiable correlation between variations in pore-water pressure and the consequent Safety Factor. This

approach provides a direct and realistic assessment of how an increase in pore-water pressure can reduce the soil's shear strength (based on the Mohr-Coulomb criterion) and, consequently, diminish the Safety Factor. The combined analysis therefore offers a more comprehensive and realistic understanding of a slope geomechanical behaviour in relation to its hydrological dynamics and potential instability. The SLOPE/W module executes a slope stability analysis grounded in the principles of geomechanics and numerical modelling. The operational methodology is based on the application of the limit equilibrium method, whose primary function is the determination of the Safety Factor. This factor is defined as the ratio between the resistances forces that oppose movement and the driving forces that initiate it.

The limit equilibrium analysis was performed using the Morgenstern-Price Method (1965).

The selection of this methodological approach is justified by its well-established recognition as one of the most balanced in terms of theoretical completeness and precision for slope stability analysis.

The Morgenstern-Price Method is based on the slices technique, which involves dividing the potentially unstable soil mass into a system of vertical columns for the stability analysis. The geometric schematisation of this subdivision is detailed in Figure 3.35.

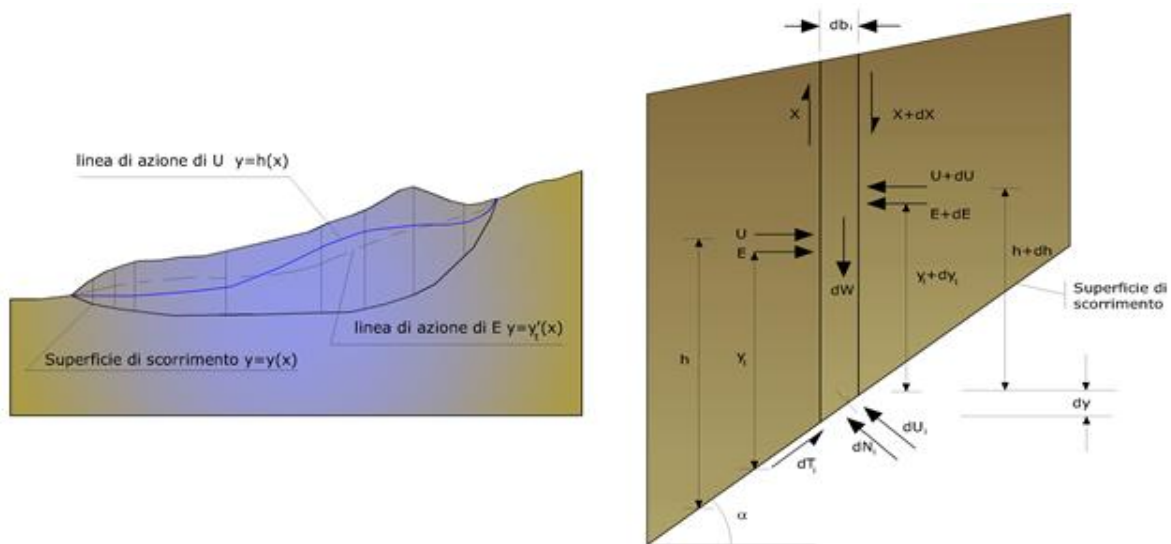


Figure 3.35 - Morgenstern-Price method: representation of the division of the slope into slices and the forces acting on the i-th slice (www.geostru.eu).

For each individual slice, the method rigorously solves both the equations of force equilibrium (the sum of horizontal and vertical forces is equal to zero) and the equations of moment equilibrium (the sum of moments of a point of rotation is equal to zero).

Consequently, for the determination of the Factor of Safety (Fs), the Morgenstern and Price method employs an iterative procedure to solve a system of equations, thereby ensuring the simultaneous satisfaction of the global force equilibrium (F_f) (eq. 30) and the moment equilibrium (F_m) (eq.31) conditions.

$$F_f = \frac{\sum(c'\varepsilon \cos\alpha + \left[N - u_w\varepsilon \frac{\tan\varphi^b}{\tan\varphi'} - u_a\varepsilon \left(1 - \frac{\tan\varphi^b}{\tan\varphi'}\right)\right] \tan\varphi' \cos\alpha}{\sum N \sin\alpha} \quad (30)$$

$$F_m = \frac{\sum c'\varepsilon + \left[N - u_w\varepsilon \frac{\tan\varphi^b}{\tan\varphi'} - u_a\varepsilon \left(1 - \frac{\tan\varphi^b}{\tan\varphi'}\right)\right] \tan\varphi'}{\sum Wx - \sum Nf} \quad (31)$$

Where ε is the angle of inclination of the slice base with respect to the horizontal, N is the total normal force on the base of the slice, W is the total weight of a slice, x is the vertical interslice shear forces and f the perpendicular offset of the normal force from the center of rotation or from the center of moments.

In the preceding equations, the acting forces including seismic actions, applied external loads, or resultant forces due to the presence of free water (such as those exerted by lakes or rivers) have not been accounted for in the denominator.

Unlike more simplified methods that ignore the interactions between slices, the Morgenstern-Price method explicitly considers interslice forces (normal, E , and shear, X). The relationship between these two forces is crucial and is defined by the function $f(x)$, which is parameterised by a scalar factor λ .

$$X = \lambda f(x) E \quad (32)$$

This formulation is a distinctive feature that allows for a physically coherent distribution of shear along the potential sliding surface.

The soil shear strength, which is necessary for the equilibrium calculations, is determined using the Mohr-Coulomb failure criterion. This criterion defines the available shear strength (τ_f) as a function of the effective cohesion (c'), the effective angle of friction (φ') and the effective normal stresses (σ_n'). In unsaturated soils, the traditional Mohr-Coulomb failure criterion is extended to incorporate the influence of the two-phase water-air system within the porous matrix. This extension relies on the introduction of additional parameters that quantify the

intergranular forces under conditions of partial saturation. The shear strength (τ) along the base of a slice in an unsaturated soil, as used in the Morgenstern and Price method, is given by the equation that includes the matric suction:

$$\tau_{f,i} = c' + (\sigma_{n,i} - u_{a,i})\tan\phi' + (u_{a,i} - u_{w,i})\tan\phi_b \quad (33)$$

The factor of safety is therefore calculated as the ratio of the available shear strength (τ_r) to the mobilized shear strength (τ_m).

$$SF = \frac{\tau_r}{\tau_m} \quad (34)$$

Therefore, the software performs an iterative process to solve the system of equations and find the SF value that simultaneously satisfies both force (F_f) and moment equilibrium (F_m) along a given surface. The software makes an initial assumption for the factor of safety (SF) and for the λ parameter, which controls the distribution of shear forces between the slices. Using these initial values for SF and λ , the software calculates all the forces and moments acting on each slice. In this case, the Mohr-Coulomb criterion and therefore the soil parameters c' , ϕ' and $(u_a - u_w)$ are fundamental for determining the mobilized shear strength. The software checks if the slope is in equilibrium (i.e., if the sum of the horizontal and vertical forces and the sum of the moments are close to zero). If equilibrium is not satisfied, the software adjusts the values of SF and/or λ and repeats the calculation. This process is repeated until the system converges, which is when the equilibrium equations are satisfied. The process is then replicated for all considered slip surfaces. The final objective of the analysis is to identify the critical surface, which is the one that produces the minimum factor of safety, representing the most probable failure configuration.

When conducting a SLOPE/W analysis, it is crucial to define the slope geometry and the initial hydrogeological conditions. In this specific case, the SLOPE/W analysis is performed using the geometry and pore-water pressure conditions derived from a SEEP/W analysis. In addition, it is necessary to implement the shear strength parameters according to the Mohr-Coulomb failure criterion, namely the effective cohesion and the effective angle of internal friction, along with the unit weight of the soil, which is fundamental for calculating the body forces acting on the soil mass. For unsaturated soils, matric suction plays a critical role. Consequently, the software models this effect by relating suction to shear strength using the Water Retention Curve (WRC), which utilises the function previously defined in the SEEP/W seepage analysis. The detailed

application of the aforementioned methodology to the specific case study will be addressed in Paragraph 5.4.

3.3.5 Fully coupled hydro-mechanical analysis - PLAXIS

In GeoStudio, geotechnical analysis using the SEEP/W and SLOPE/W modules evaluates how hydrological variations influence the limiting stability of a slope. While this approach is effective for determining the slope's factor of safety in response to varying saturation conditions, it has a fundamental limitation. The analysis focuses exclusively on the effect of changes in pore-water pressures within the soil. Although these pressures are a critical factor for stability, the method does not consider soil deformations and displacements specifically, the volume changes directly induced by hydrological variations.

Consequently, for a comprehensive assessment that also includes the deformational behaviour of the terraced system, a coupled flow-deformation analysis was performed using the finite element software PLAXIS (Bentley Systems, version 2D CONNECT Edition V21). This analysis simultaneously solves the equations that govern water flow (continuity equations) and those that describe the mechanical behaviour of the soil (equilibrium equations). In this way, changes in pore pressure and soil deformations influence each other. This complex analytical dynamic provides more detailed information on the lateral pressures exerted by the soil on the structure and their interaction in response to hydrological changes.

This analysis was conducted exclusively for site 850 because it's the only one of the three sites where pressure cells were installed, which allows for a qualitative comparison with the lateral total pressures generated by the coupled analysis. The analysis has further allowed for the detailed definition of the vegetation's contribution in terms of its effect on the total horizontal stresses imparted by the soil upon the retaining structure.

For the correct execution of a finite element geotechnical analysis, particularly a coupled (flow-deformation) type, it is necessary to set up a preliminary phase in PLAXIS that is representative of the in situ initial stress state. To achieve this objective, a dedicated calculation phase was carried out to generate the initial conditions.

This phase is not a coupled analysis, but rather a fundamental step for establishing an equilibrium state in the numerical model before the application of external loads. The primary objective is to calculate the distribution of total stresses (σ), effective stresses (σ') and pore-water pressures (p_{active}) in the soil before the external load due to precipitation begins to be applied. The type of preliminary analysis performed to generate the model's initial conditions

is Gravity Loading. This type of initial analysis was deemed more appropriate than a K0initialisation procedure, as the adopted approach naturally accounts for the slope inclination and the geometrical distribution of volumetric loads within each finite element. This results in a more realistic stress state that is compatible with the model's inclined geometry. Conversely, K0-based initialisation is unable to accurately model the complex stress redistribution that occurs in a slope. This analysis realistically establishes the in situ initial stress conditions of the model. This method is based on a rigorous physical approach, where the model's initial equilibrium is achieved by allowing gravitational forces to act on the soil mass. The computational process initiates a calculation phase where gravity forces ($\rho \cdot g$) are gradually and controllably applied to the entire geometry of the model, acting on each single finite element. The software solves the equilibrium equations, allowing the model to deform until the internal stresses perfectly balance the gravitational forces, reaching a stable equilibrium condition. The analysis will therefore provide a complete and consistent definition of the initial conditions based on the geotechnical model set up in the pre-analysis phase, which will serve as the basis for the subsequent coupled flow analysis.

The fully coupled analysis for unsaturated soils is based on two fundamental equations: the equilibrium equation and the continuity of flow equation. The finite element implementation of these equations leads to a non-linear matrix system that is solved simultaneously.

The equilibrium equation for unsaturated soil is based on Bishop effective stress concept, which includes both air pore pressure (p_a) and water pore pressure (p_w). The equation is defined as (Galavi et al., 2009):

$$\sigma = \sigma' + m (\chi p_w + (1 - \chi) p_a) \quad (35)$$

Where σ is the total stress vector, σ' is the effective stress vector, m is a vector containing unity terms for the normal stress components and zero for the shear stress components, and χ is the matric suction coefficient, a parameter that varies from 0 (for completely dry soil) to 1 (for completely saturated soil).

In PLAXIS 2D, χ (the matric suction coefficient) is considered equal to S_{eff} (the effective degree of saturation), therefore, the Bishop's effective stress in PLAXIS 2D is:

$$\sigma' = \sigma - S_{eff} (p_{steady} + p_{excess}) = \sigma - p_{active} \quad (36)$$

In soil mechanics, p_{steady} represents the hydrostatic or steady-state pore water pressure that develops in the ground, while p_{excess} is the excess pore pressure that occurs due to an external

load or undrained action. The sum of these two pressures, p_{water} , defines the pore water pressure in the soil.

p_{active} , on the other hand, is defined as the component of water pressure that effectively acts on and influences the effective stresses within a soil, thereby determining its shear strength and deformability. This is especially crucial in unsaturated soils, where p_{active} does not necessarily coincide with the total pore water pressure (p_{water}). Instead, it represents the component that exerts an actual force on the solid soil matrix. p_{active} is therefore a product of the effective saturation (S_{eff}) and the pore water pressure (p_{water}) (Bentley Systems, 2024).

The relationship between soil suction and the degree of saturation is described by the van Genuchten equation, which in PLAXIS is expressed as:

$$S(\Psi) = S_{\text{res}} + (S_{\text{sat}} - S_{\text{res}})[1 + (g_a|\Psi|)^{g_n}]^{g_c} \quad (37)$$

Where $\Psi = -\frac{p_w}{\gamma_w}$, p_w is the matric suction in the pores, γ_w is the unit weight of the pore fluid, and S_{res} is the residual saturation, which represents the fluid that remains in the pores even at high suction values. S_{sat} is the degree of saturation under fully saturated conditions. g_a is a fitting parameter related to the air entry value of the soil, while g_n is a fitting parameter that depends on the rate of water extraction from the soil after the air entry value has been exceeded. g_c is another fitting parameter used in the general van Genuchten equation, where $g_c = (1 - g_n)/g_n$. The continuity equation for flow, as implemented in PLAXIS for coupled analysis, is represented by the following expression (neglecting solid particle deformations and water density gradients (Boussinesq approximation) (Galavi et al., 2009)).

$$\nabla^T \left[\frac{k_{\text{rel}}}{p_w g} k_{\text{sat}} (\nabla p_w + p_w g) \right] + S m^T \frac{\delta \varepsilon}{\delta t} - n \left(\frac{S}{k_w} - \frac{\delta S}{\delta p_w} \right) \frac{\delta p_w}{\delta t} = 0 \quad (38)$$

The first term represents the divergence of hydraulic flux, while the second term accounts for the change in water content within the fundamental calculation element due to the deformation of the solid matrix. The third term incorporates both the compressibility of the water and the water retention curve (WRC). k_{rel} and k_{sat} refer to the relative and saturated permeabilities respectively. k_w is the bulk modulus of water. In PLAXIS, the relative permeability (k_{rel}) is related to the pore suction pressure by the following expression (PLAXIS 2D, 2024):

$$k_{rel}(S) = \left[(S_{eff})^{gl} 1 - \left[(1 - S_{eff})^{\left(\frac{1}{g_c}\right)} \right]^{(-gc)} \right]^2 \quad (39)$$

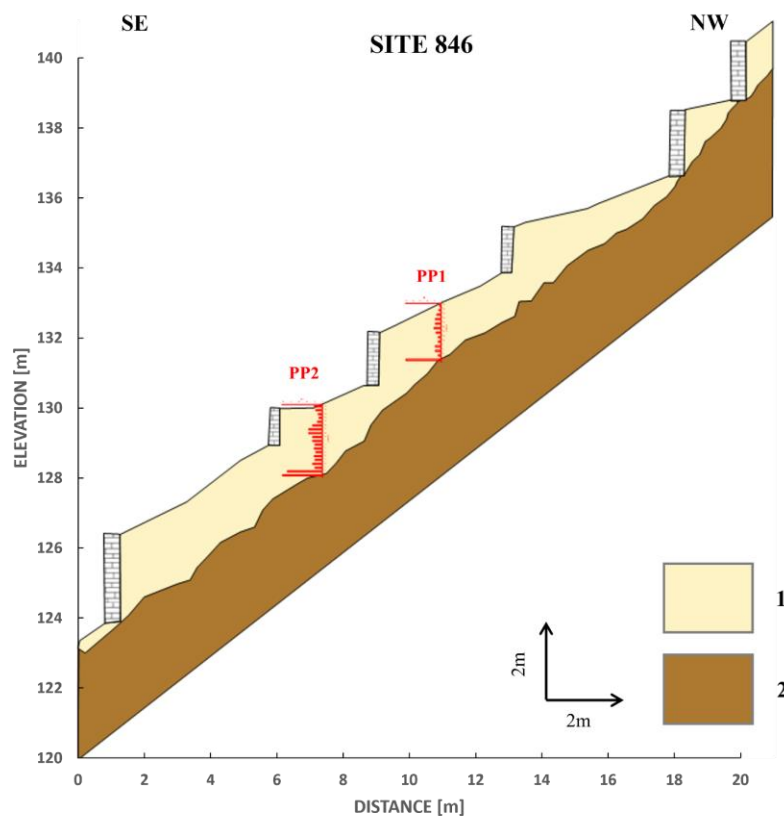
gl is a calibration parameter, and Se is referred to as the effective saturation (Paragraph 3.3.1.1, eq.8). Consequently, to perform a coupled analysis, the two equations, deformation and continuity, are combined into a single block matrix system that is solved simultaneously at each time step. This system is highly non-linear due to the elasto-plastic behaviour of the soil, the dependence of suction on the degree of saturation, and the dependence of permeability on suction.

To ensure the robustness of the model, the hydrological component incorporated into the coupled analysis in PLAXIS was derived from the previous validation performed with the GeoStudio software, using the SEEP/W module. This preliminary phase was crucial for ensuring that the flow conditions and the pore water pressure distribution were simulated with the highest precision. This made it possible to provide the necessary hydraulic boundary conditions for the coupled mechanical analysis in PLAXIS, guaranteeing the reliability of the results. The detailed application of the aforementioned methodology to the specific case study will be addressed in Paragraph 5.5.

CHAPTER 4 – RESULTS OF GLOBAL SCALE ANALYSIS

4.3 DEVELOPMENT OF GEOTECHNICAL MODEL

Thanks to the joint interpretation and integration of the whole set of data acquired from both field and laboratory tests (APPENDIX 1-2), it was possible to reconstruct 2D engineering-geological models of the selected slope segments. These models consist of three engineering-geological cross sections (Figures 4.1) which represent the stratigraphic setting of each investigated sites, enabling to outline the main hydrological and geotechnical feature. Two main geological units were identified for each investigation site (Figure 4.1): anthropic-reworked eluvial-colluvial soil cover layer (Layer 1) and bedrock (Layer2).



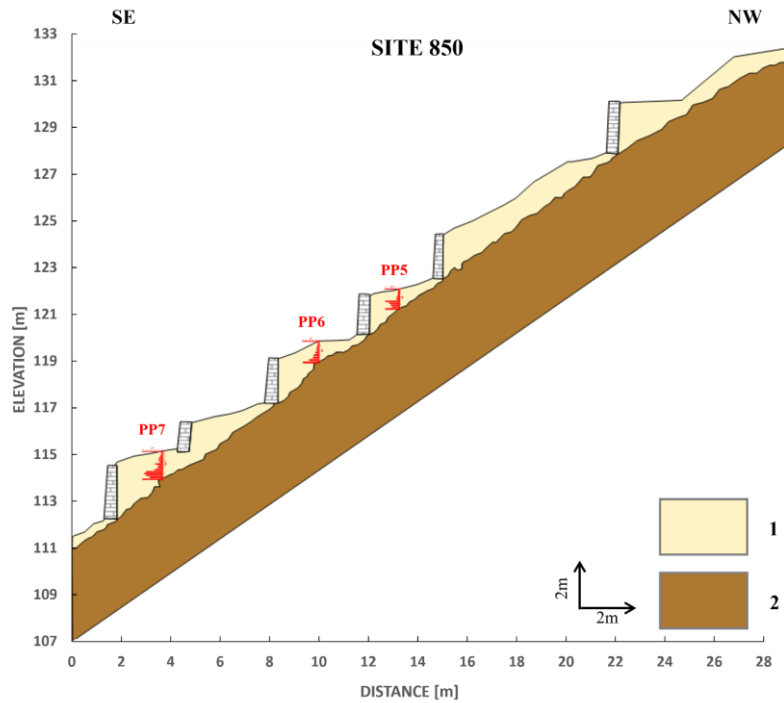
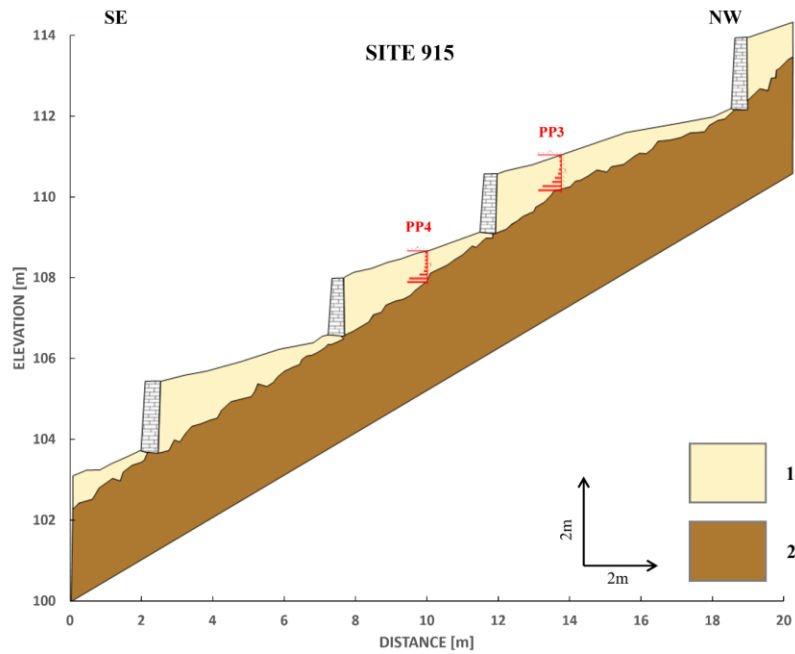


Figure 4.1 - 2D engineering-geological models of the selected investigation sites.

The seismic surveys suggested the presence of a single low-velocity layer overlying the bedrock. This setting was constrained by the results of direct investigation, namely dynamic probing tests. These latter tests revealed a certain variability in N_{10} that was attributed to different degrees of compaction across depth. This interpretation was supported by the

similarity of physical- mechanical parameters determined from both in-situ and laboratory tests (Table 4.1), justifying the choice to model the superficial material as a single geotechnical layer.

Table 4.1 - Summary of physical and mechanical parameters for the three investigation sites. *Dr*: relative density; ϕ : friction angle; γ_{nat} : natural unit weight; γ_{dry} : dry unit weight; γ_{sat} : saturated unit weight; W_n : natural water content; k_{sat} : saturated permeability; *IP*: plasticity index; *n*: porosity; *e*: void ratio and *O.C.*: organic content.

	SITE	D_r (%)	ϕ' (°)	γ_{nat} kN/m ³	γ_{dry} kN/m ³	γ_{sat} kN/m ³	W_n %	k_{sat} m/s	<i>IP</i> %	<i>e</i> -	<i>n</i> -	<i>O.C.</i> %
	846			14,9	14,6	19,1	2,2		4,5	0,85	0,46	4,4
Layer 1	915	24,25	32	15,9	15,3	19,5	3,9	2,39E-04	3,6	0,76	0,43	3,4
	850			13,3	12,6	17,8	4,8		4,9	1,1	0,53	7

Soil thicknesses vary depending on the extent of anthropic reworking, especially related to the agricultural terrace construction, and the irregularities of the bedrock surface morphology. However, soil thickness mostly increases from the internal edge of the terrace benches (i.e., at the base of the upslope dry-stone wall) towards the external edge (i.e., behind the downslope wall face). In the first case, soil thicknesses of about 40-50 cm were defined, while, in the second case, the thickness resulted in the order of 1.5-2.0 m, depending on the masonry heights. From the comparative analysis of the three engineering-geological models, some morphological and structural differences can be inferred. At sites 846 and 850, a higher average slope inclination than at Site 915 occurs. The thickness of the reworked eluvial-colluvial soil cover is on average slightly greater at sites 850 and 846. Moreover, at Site 915 the wall foundations seem to directly rest on the bedrock, presumably conferring high basal stability. Conversely, at site 846 and 850, some wall foundations may be partially or totally embedded within the colluvium.

Based on the analysis of Table 4.1, the investigated soil covers can be assumed as coarse-grained, porous, loose and characterized by low plasticity, clearly indicating a pronounced permeable character. The indirect estimates of shear strength properties were found to be typical of coarse-grained and cohesionless soils.

4.2 NUMERICAL MODEL SETUP

A slope stability analysis was conducted using the Finite Element Method (FEM) software, by taking into account the morphological, stratigraphic, and engineering-geological slope settings outlined in Section 4.3. The geometric and engineering-geological parameters and features of each investigated site were accurately implemented within the ADONIS software. To this end,

three principal materials were identified (Figure 4.2): i) anthropically reworked soil cover, ii) dry-stone wall blocks, and iii) bedrock.

For each material, a constitutive model representative of the mechanical behaviour was attributed. For the anthropically reworked eluvial-colluvial superficial deposits and for the blocks constituting the dry-stone wall, an elasto-perfectly plastic model based on the Mohr-Coulomb (MC) failure criterion was employed. The choice of this model reflects the importance in simulating potential shearing instability mechanisms. In contrast, the bedrock was modelled with an isoelastic (ISE) behaviour, since it was assumed as a rigid material that will not reach failure conditions. This simplification is justified by its high relative mechanical strength compared to the superficial layers and by the purpose of the modelling. Table 4.2 summarizes the associated mechanical parameters assigned to each layer. The elastic parameters (i.e., Young Modulus and Poisson' Ratio) were defined for the calculation of deformations and the initial stress state, while the strength was governed by the c' and ϕ' parameters. In this analysis, the contribution of the different types of vegetation was considered by assigning a different root cohesion to the soil cover layer, representative of the land use conditions at each site. The root cohesion data were defined based on a careful review of the literature related to conditions similar to those of the study area (Raimondi et al., 2023).

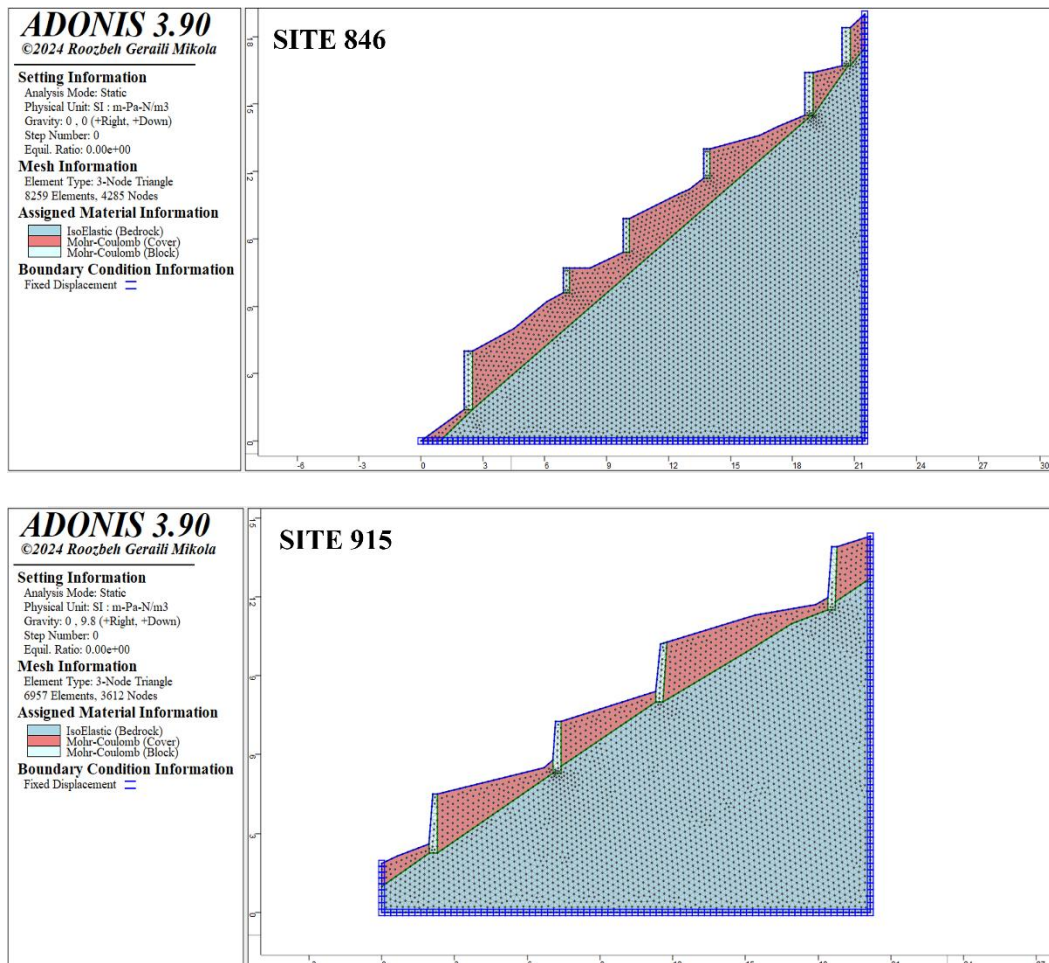
Table 4.2 - Physical and mechanical parameters assigned to the geomaterials considered for the stability analysis.

	SITE 915			SITE 846			SITE 850		
	Bedrock	Cover	Block	Bedrock	Cover	Block	Bedrock	Cover	Block
	ISE	MC	MC	ISE	MC	MC	ISE	MC	MC
ρ (kg/m^3)	2500	1600	2 500	2500	1300	2 500	2500	1500	2 500
E (Pa)	$6,70 \cdot 10^9$	$1,50 \cdot 10^7$	$6,70 \cdot 10^9$	$6,70 \cdot 10^9$	$1,50 \cdot 10^7$	$6,70 \cdot 10^9$	$6,70 \cdot 10^9$	$1,50 \cdot 10^7$	$6,70 \cdot 10^9$
ν (-)	0,20	0,30	0,20	0,20	0,30	0,20	0,20	0,30	0,20
c (Pa)	/	2800	$1,80 \cdot 10^7$	/	1600	$1,80 \cdot 10^7$	/	1000	$1,80 \cdot 10^7$
ϕ (°)	/	32	50	/	32	50	/	32	50

In order to simulate the mechanical properties of dry-stone walls, which is characterised by the presence of interconnected rock blocks, discontinuities were introduced between the intact rock elements. An angle of internal friction of 20° was assigned to each of these discontinuities, which is related to the roughness of the blocks, along with normal and shear stiffnesses of 2.0×10^9 Pa/m.

Subsequently, the geometric model was discretised by generating the mesh. This process constitutes a crucial stage in Finite Element Method (FEM) analysis, as it is essential to ensure the accuracy and stability of the numerical solutions obtained. Specifically, the mesh was created using three-noded triangular elements. This choice was connected to the notable versatility of these elements in adapting to complex slope geometries and their robustness in modelling plasticisation and deformation phenomena. To each triangular element an area of 0.25 m² was assigned (Figure 4.2).

In order to ensure an accurate simulation of the slope behaviour and for the rigorous definition of the limit state within the computational domain, specific displacement boundary conditions (kinematic constraints) were imposed at the model edges. Specifically, a “fix xy” constraint condition was adopted for both the lateral boundaries of the profile and the lower boundary (Figure 4.2). This implies blocking the boundary along both displacement components, namely the horizontal ($u_x = 0$) and the vertical ($u_y = 0$). The upper boundary remained unconstrained.



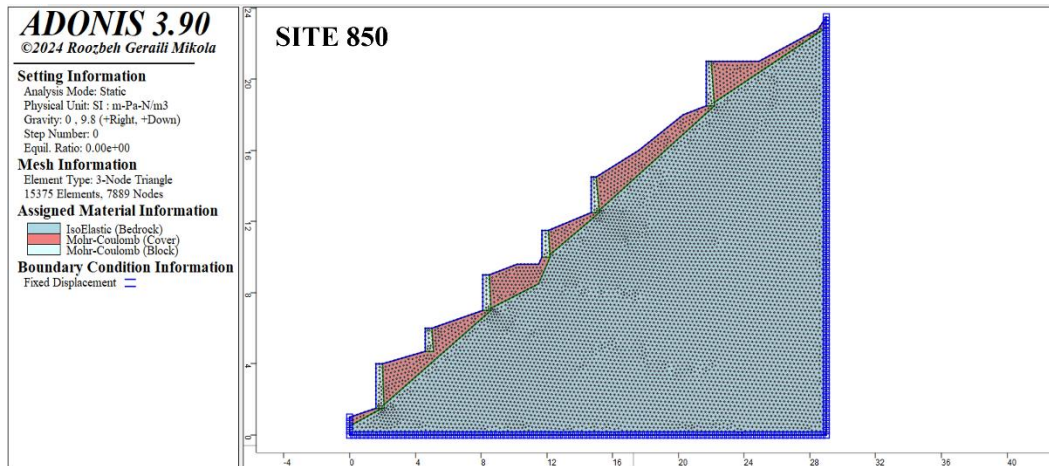
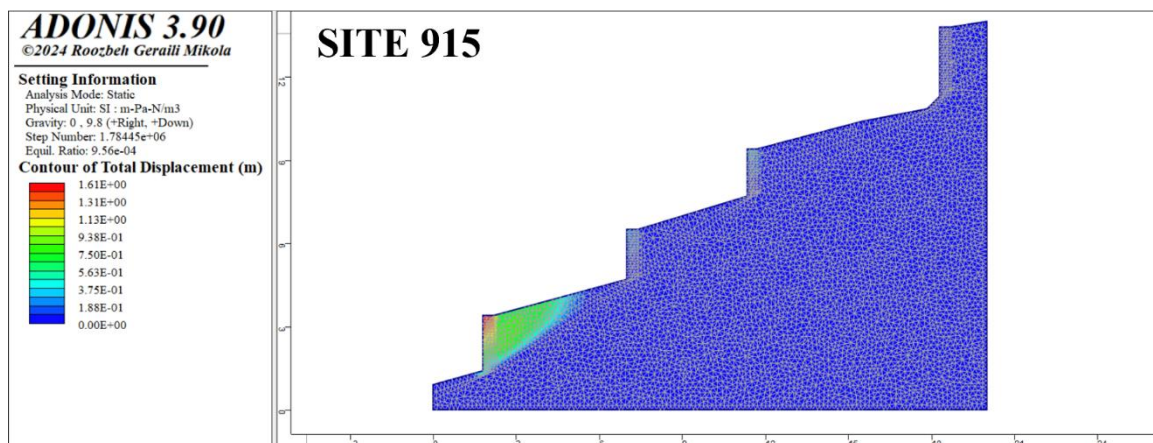


Figure 4.2 - Numerical models implemented for the strength reduction stability analysis in the upper right corner of each panel, information on the modelling type, mesh characteristics, materials, and kinematic boundary conditions is reported.

The analysis proceeded with model initialization, through which the initial geostatic conditions were determined and subsequently by performing a strength reduction analysis.

4.3 STABILITY ANALYSIS RESULTS AND DISCUSSION

The stability analysis at the slope scale revealed significant differences in the mechanical behaviour of the selected slopes. The results, presented in terms of displacement distribution (Figure 4.3), allow for a critical comparison.



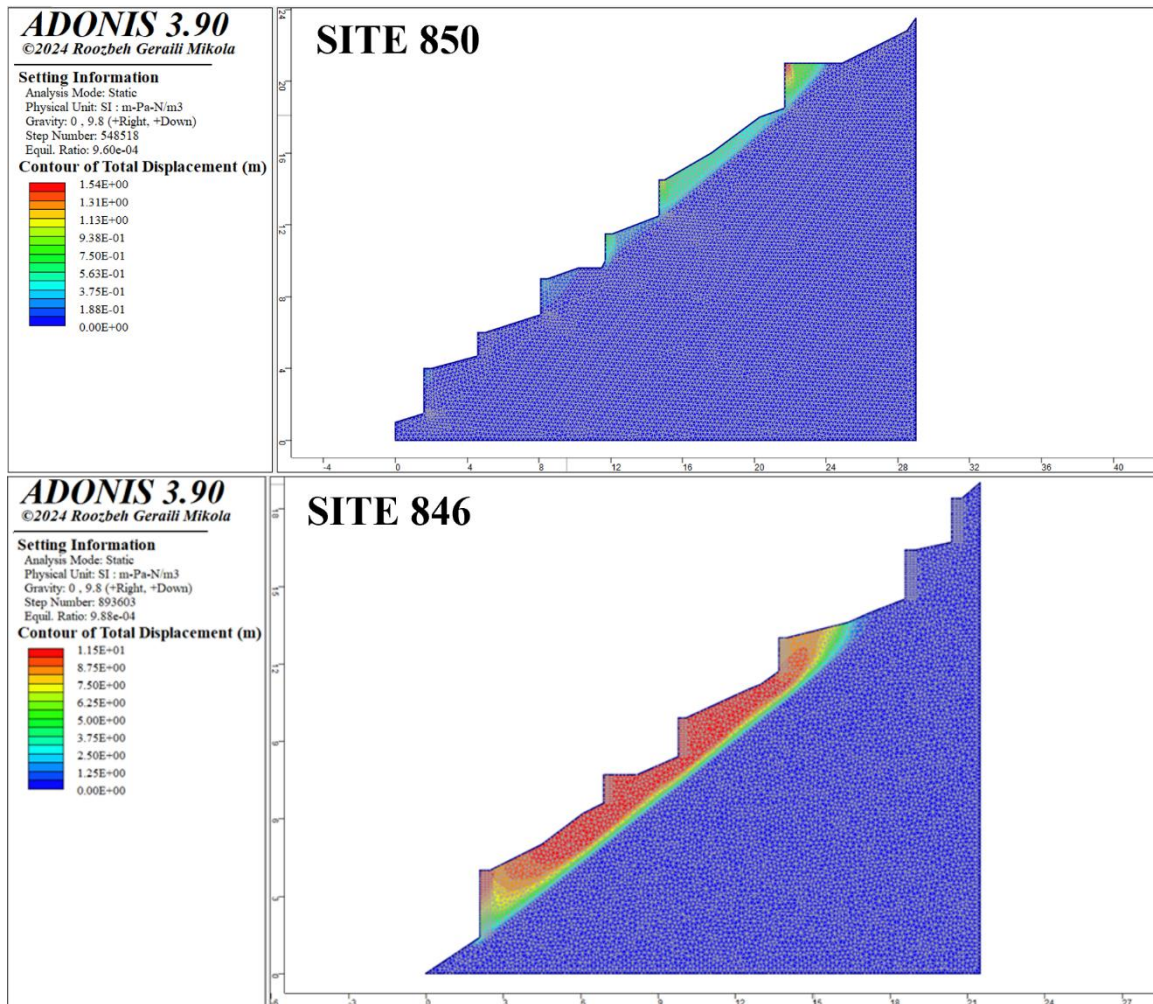


Figure 4.3 - Results of the stability analysis expressed in terms of displacement distribution.

From this comparison, two substantial differences related to the deformational response of the slopes has been outlined: the first concerns the spatial distribution of strain, while the second one relates to the strain magnitude.

This distinction allows the analysis results to be divided into two categories:

1. **Slope-scale instability (Site 846):** This mechanism is characterised by movement involving the entire slope and associated with a displacement magnitude an order of magnitude greater than that observed at the other sites.
2. **Localised instability (Sites 850 and 915):** This manifests as deformation confined to a restricted zone of the slope. In this scenario, the magnitude of the displacement is comparatively smaller, suggesting a condition of potential failure that affects only the single terrace-dry stone wall system.

The instability detected in both contexts affects only the surface layer of the soil. It is therefore assumed that the factors determining this instability have a different effect depending on the site analysed. For example, at Site 846, the instability is global in nature and is linked to the presence of a surface wall structure resting on a substrate with poor mechanical properties. On the contrary, the local instability found at Sites 850 and 915 cannot be attributed to the wall, as it is founded on bedrock, a highly resistant material. In the latter scenario, stability is primarily influenced by the root cohesion of the soil, the geometry and the slope inclination. Site 915 benefits from greater stability thanks to the extremely high root cohesion of the topsoil, which gives the soil sufficient mechanical resistance to slow down the speed of movement. Added to this is a further stabilising factor: a less steep slope. At Site 850, on the other hand, the lower degree of root cohesion of the surface layer – a consequence of the recent abandonment of the slope – did not provide the necessary resistance to contrast the phenomenon. This favoured a greater spread of local instability, further facilitated by steeper slopes. Despite this, the displacement values recorded are similar to those at Site 915, indicating comparable overall stability. In summary, the differences in stability between the three sites are due to a complex combination of factors. The nature and extent of instability are determined by the combination of the slope angle, the root cohesion provided by the covering layer and, crucially, the type of foundation material used for the dry-stone walls.

CHAPTER 5 – RESULTS DETAILED SCALE INVESTIGATION

5.1 DATA QUALITY ASSESSMENT

Prior to the hydrological and mechanical analyses, a Data Quality Assessment procedure aimed at ensuring the reliability and robustness of the monitoring data was performed. In this regard, it is important to underscore that all the acquired monitoring data are characterised by an hourly frequency.

5.1.1 Meteorological data

The monitoring data for the weather variables cover a period of approximately one and a half year, specifically from August, to 2023 until November 30, 2024. To ascertain the precision of the measurements, some parameters recorded by the local station were compared with the values from the Corniolo - Riomaggiore (SP) station, which belongs to the rain gauge network of the Liguria Region Hydro-Meteorological Observatory and that is situated approximately 0.7 km away (Figure 5.1). This comparison focused on the three main parameters available from both stations, namely precipitation, atmospheric temperature, and wind speed.

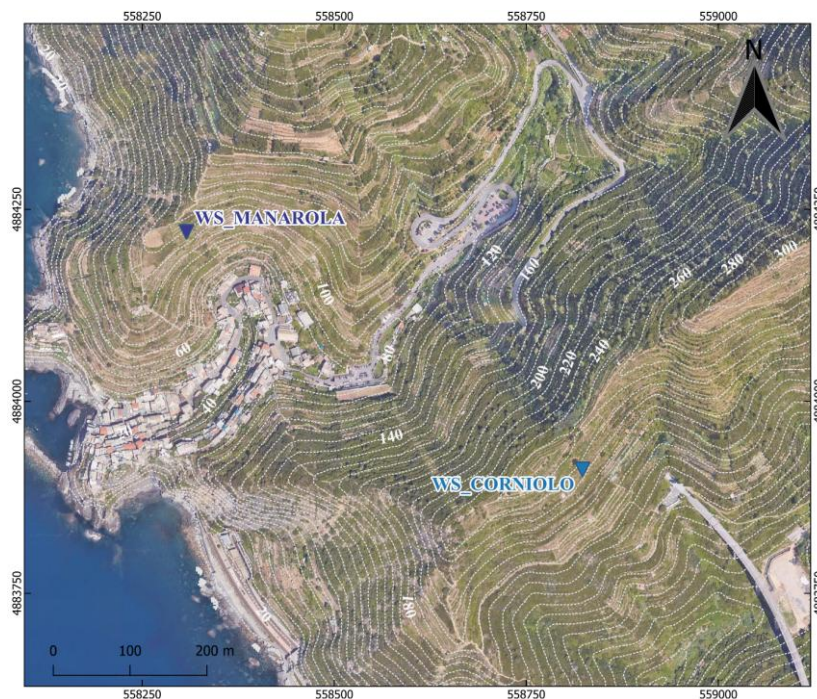


Figure 5.1 - Location of the Manarola (SP) and the Corniolo (SP) weather stations.

For the parameters for which a direct comparison was not possible, namely relative humidity and solar radiation validation, a cross-analysis was carried out. The consistency of this data was evaluated in relation to the other monitored climatic parameters, ensuring a comprehensive and integrated quality control.

- **Precipitation data**

The precipitation trend appears consistent and free of significant anomalies as data show high continuity, without any interruptions or gaps that would indicate a sensor malfunction (Figure 5.2).

A marked seasonality is observed, with more frequent and intense precipitation peaks recorded in the autumn and winter months. The maximum rainfall value was 98.643 mm. In contrast, the summer months show a sharp decrease in rainfall events, with a period of drought detected from late June to late August 2024, during which no significant precipitation levels were recorded.

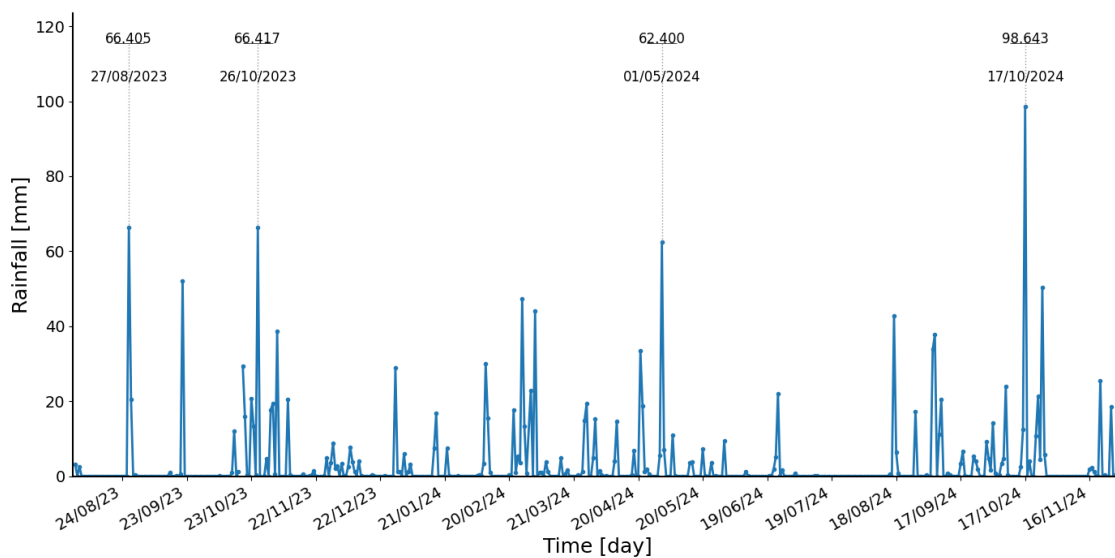


Figure 5.2 - Precipitation data recorded during the monitoring period.

This comparative analysis with the Corniolo's station was conducted over a six-month period, from January to June 2024, using as a reference the data available on the real-time monitoring website: <https://www.meteonetwork.eu/it/weather-station/lig135-stazione-meteorologica-dicorniolo/archive>. The comparison of the historical series demonstrated that the two stations show a strong correlation in their trends. Consequently, the measurements from the Manarola's station were found to be reliable and consistent with those from Corniolo (Figure 5.3). The slight differences observed fall within the normal spatial variations expected for rainfall events.

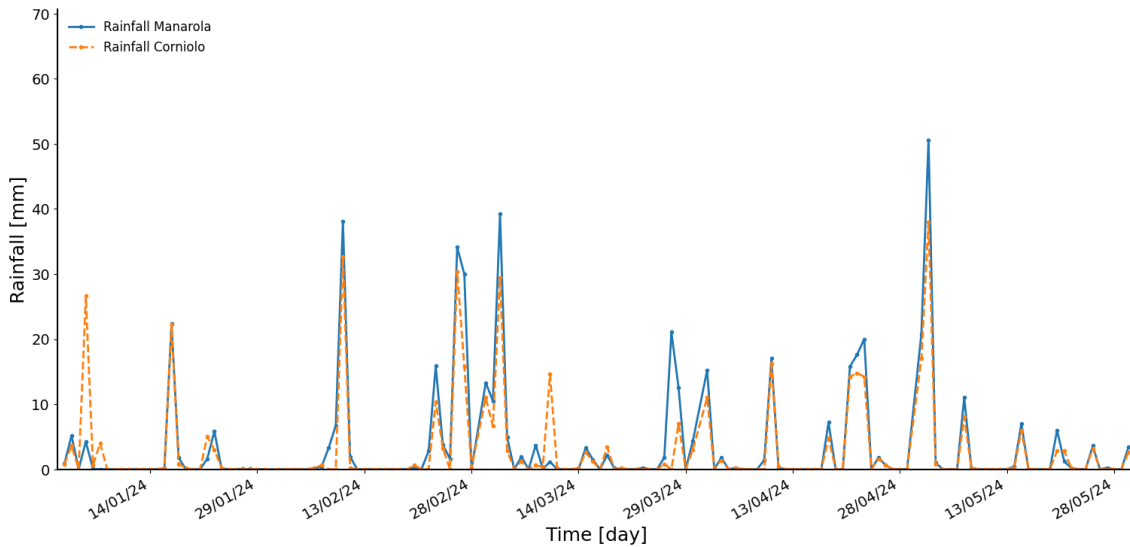


Figure 5.3 - Comparison between the precipitation recorded by the rain gauges of Corniolo and Manarola.

- **Atmospheric temperature data**

The data trend for atmospheric temperature is continuous, consistent, and free of significant anomalies. The fluctuations in daily maximum temperatures accurately reflect the expected seasonality for the area under consideration (Figure 5.4). The absence of unusual deviations or interruptions suggests that the sensor and data acquisition system are functioning correctly.

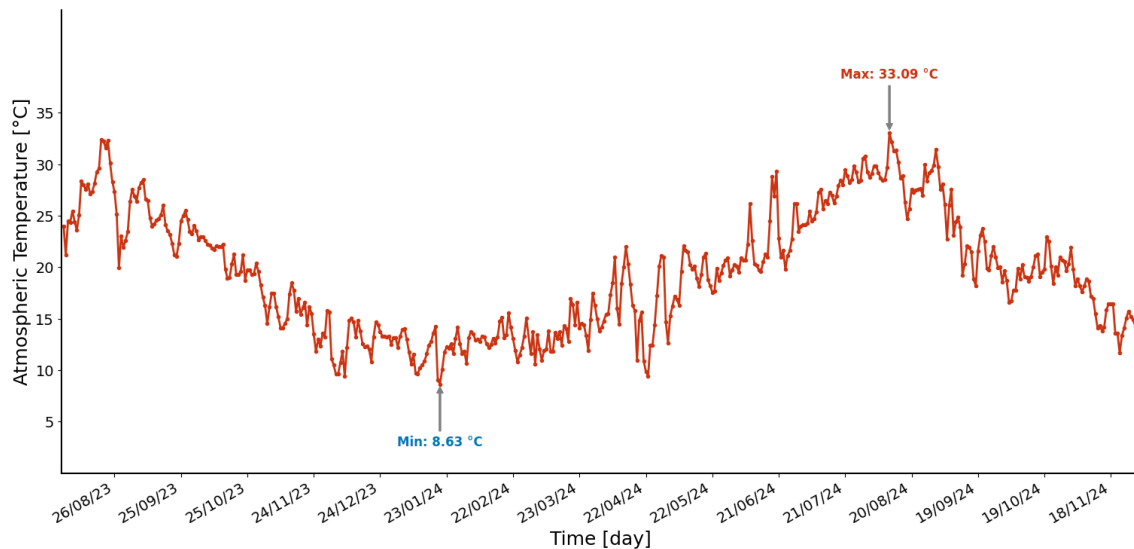


Figure 5.4 – Atmospheric temperature data recorded during the monitoring period.

The comparison of maximum temperature data recorded by the Manarola and the Corniolo (SP) stations from January 2024 to June 2024 revealed a notable similarity in their trends. The two

historical series show a strong correlation: daily average temperature curves follow almost identical trajectories, faithfully reflecting the progressive seasonal temperature increase typical of the transition from late winter to early summer (Figure 5.5).

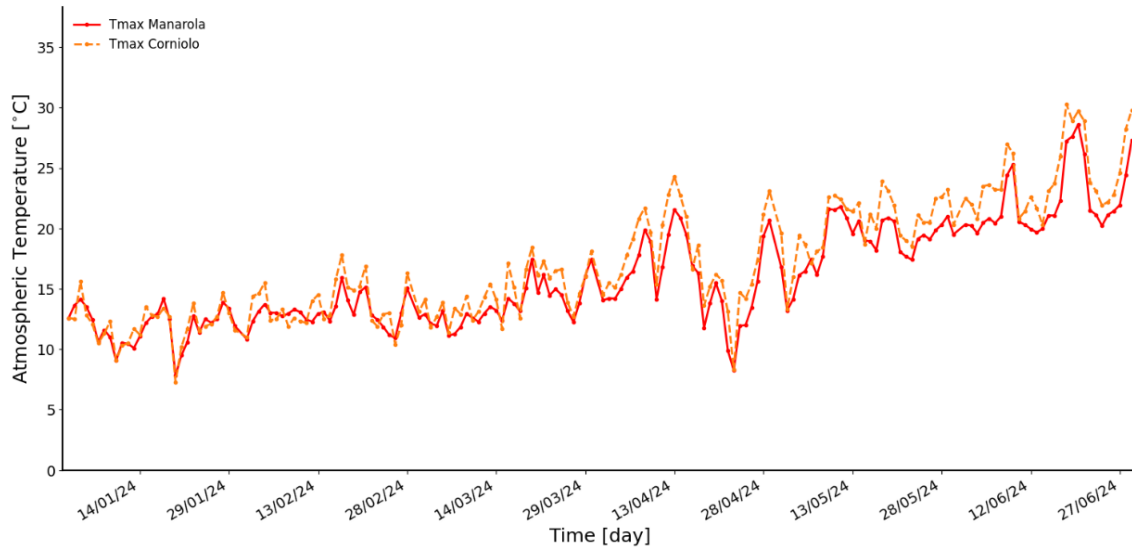


Figure 5.5 - Comparison between the atmospheric temperature recorded by the Corniolo and the Manarola stations.

- **Wind speed data**

A preliminary analysis of the raw wind speed data highlighted several anomalies, rendering the dataset unsuitable for direct interpretation. Specifically, some negative velocity values were found. This phenomenon suggests an inherent error in the data acquisition or processing, likely due to sensor inaccuracies in conditions of zero or extremely low wind (known as background noise). To address this issue, a data quality control and cleaning procedure was implemented. A correction based on a flooring procedure was adopted: all wind speed values below 0.1 km/h were set to this minimum value (Figure 5.6). This methodology assumes that negative, or near-zero values are the result of instrumental inaccuracies, such as background noise, under conditions of zero or extremely low wind.

The 0.1 km/h threshold was chosen to stabilise the dataset, ensuring that all values used for subsequent analyses were physically plausible. In this way, valid low-wind measurements were not significantly altered, allowing for a more accurate and reliable analysis.

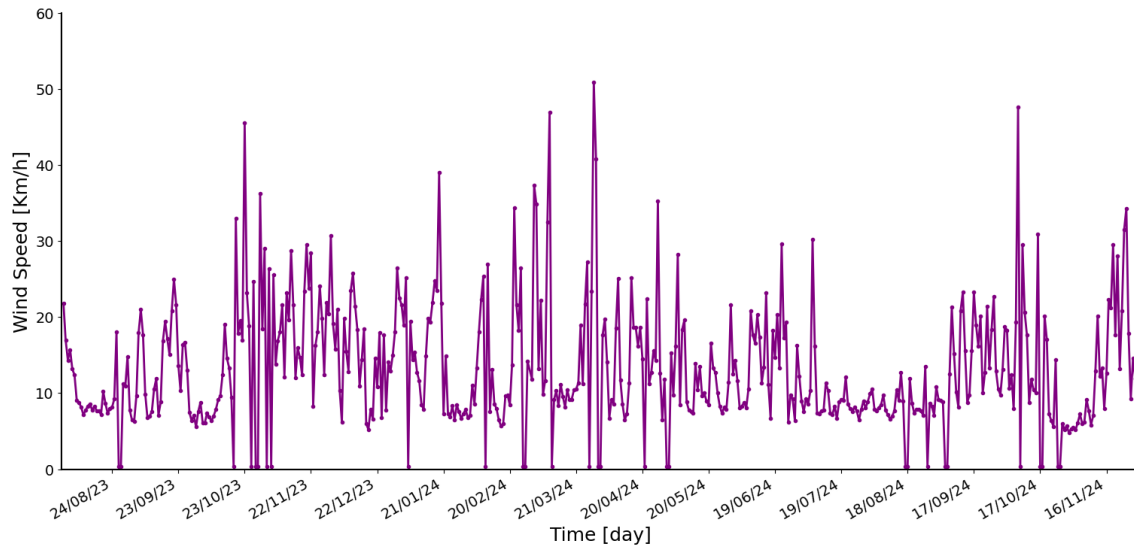


Figure 5.6 - Wind speed data corrected with the flooring procedure.

To validate the effectiveness of the correction procedure and the data trend, the historical series of maximum wind speed was compared with the equivalent values recorded by the Corniolo (SP) weather station (Figure 5.7).

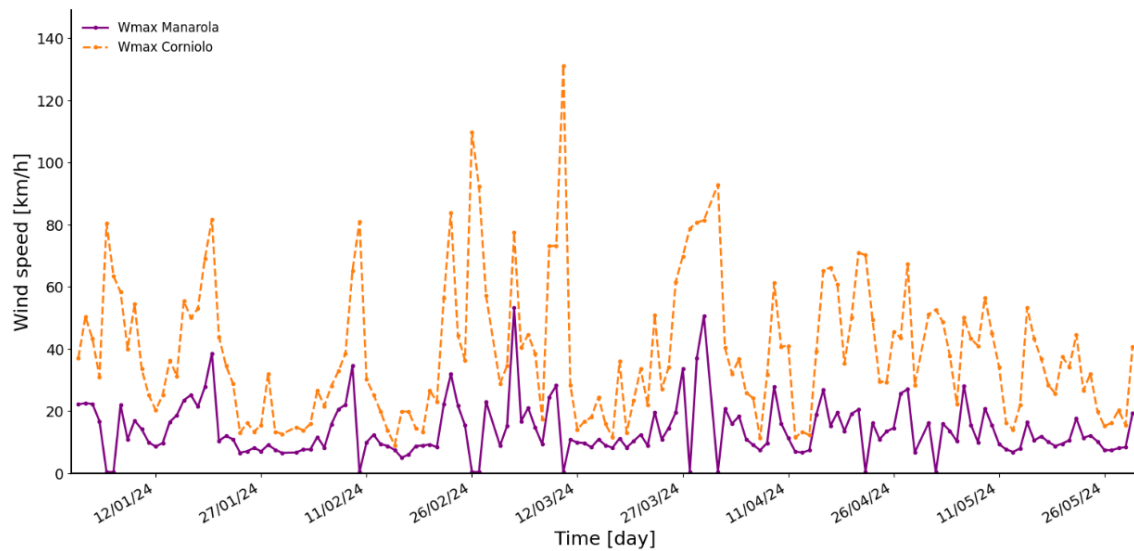


Figure 5.7 - Comparison between the wind speed recorded by the Corniolo and the Manarola stations.

The comparison revealed a strong correlation in the trend between the two stations, but a certain variability in terms of wind speed peaks, suggesting the influence of local meteorological factors. Differences in magnitude are attributed to local topographical factors. Specifically, the Corniolo station is more exposed to wind and is located at significantly higher elevation (238

m) than the Manarola station (115 m), which partly is shielded by a natural amphitheatre, thus justifying the lower wind speed.

- **Relative air humidity data**

The relative humidity data were recorded with good continuity throughout the entire period, without significant interruptions, confirming the regularity of the measurements.

The recorded values, which fluctuate between 30% and 100%, are fully compatible with the normal expected fluctuations for the study area (Figure 5.8). This assessment aligns with the methodologies for validating hydro-meteorological data established by the "Guidelines" of the SNPA (National System for Environmental Protection), ensuring the reliability of the dataset.

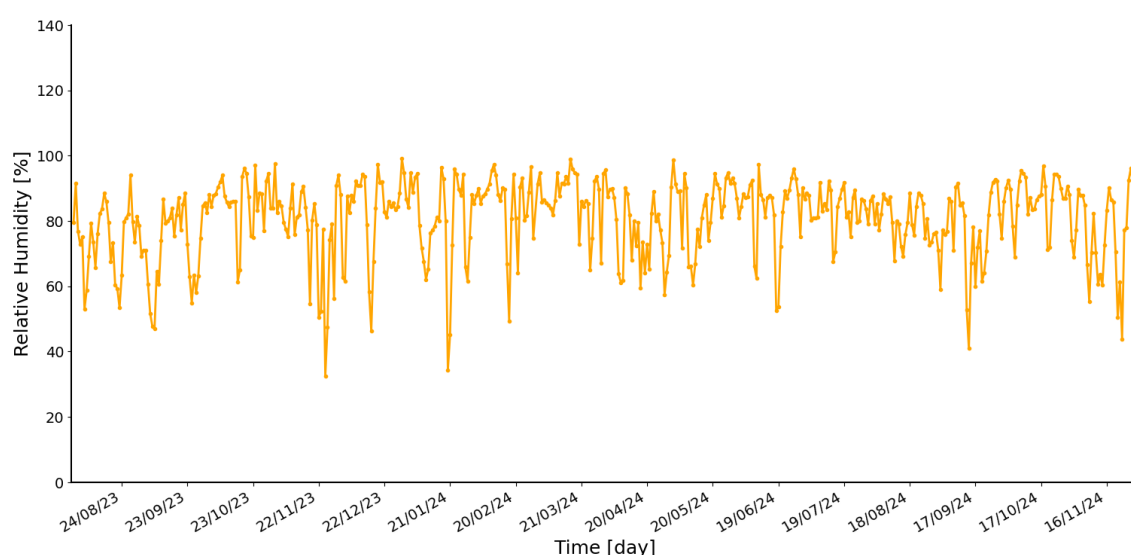


Figure 5.8 – Relative humidity data recorded during the monitoring period.

The reliability of the data was assessed by creating a comparison graph between relative humidity and precipitation, based on the close correlation between these two variables (Figure 5.9). For a more detailed analysis of data quality, a specific period within the two-year time series was examined.

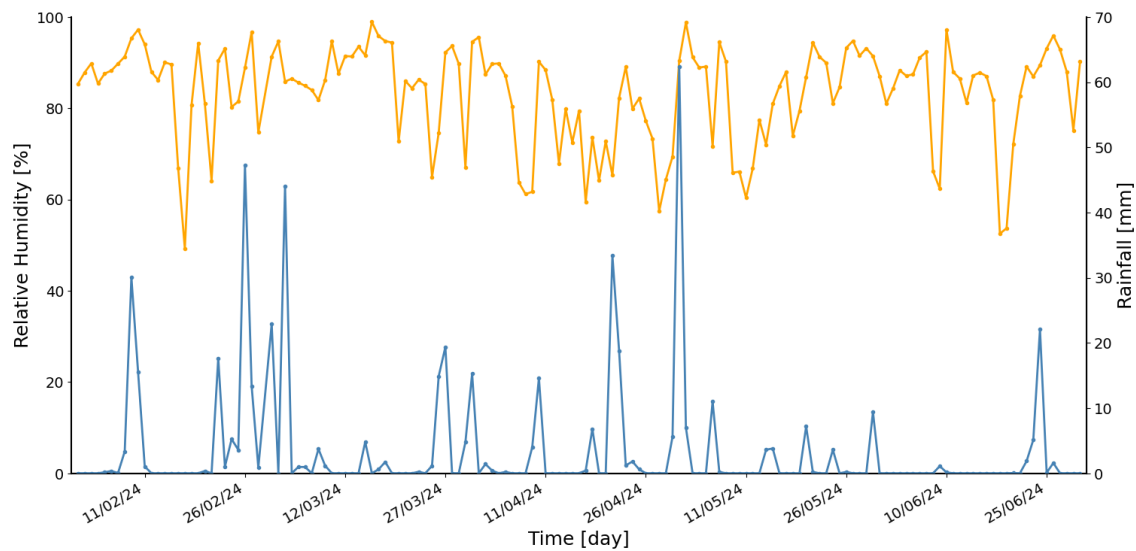


Figure 5.9 - Comparison between relative humidity and atmospheric temperature recorded by the Manarola station.

The graphical comparison highlights a positive correlation between humidity and precipitation: each rainfall event corresponds to a peak in maximum relative humidity, which tends to approach 100%. The highest precipitation peaks are unequivocally associated with very high humidity values, confirming that rain originates from air saturated with water vapour.

- **Solar Radiation data**

The historical data series of solar radiation is continuous and free from significant interruptions, confirming the reliability of the monitoring system. A clear seasonal cyclical trend is evident, with maximum values recorded in late spring and summer (April-July) corresponding to a greater solar incidence, and minimum values in autumn-winter (October-February), with a negative trend near the winter solstice (Figure 5.10). The maximum solar radiation values, ranging from 350 to 450 W/m², are considered plausible and in line with expectations for a location like Manarola, as confirmed by the Italian Solar Radiation Atlas from ENEA. The absence of anomalies or extreme values suggests the sensor is free from malfunctions.

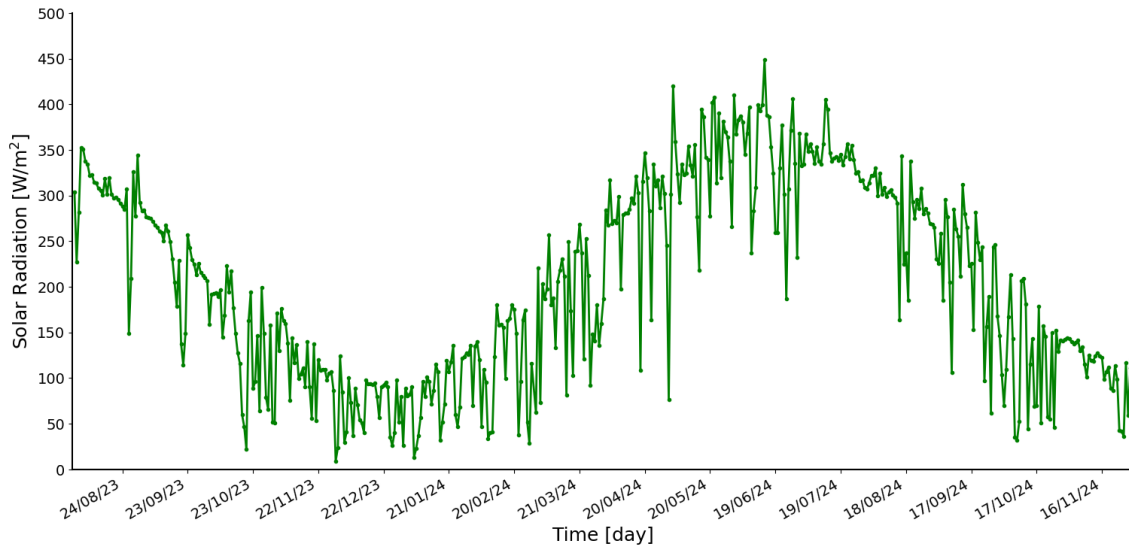


Figure 5.10 – Solar radiation data recorded during the monitoring period.

For a further validation, the solar radiation data were compared with the previously validated atmospheric temperature data. The comparison between the maximum atmospheric temperature (AT_{max}) and the maximum solar radiation (SR_{max}) shows a strong and direct correlation (Figure 5.11). However, a natural time lag is observed: the temperature peaks occur slightly after the solar radiation peaks. This physical phenomenon is due to the absorption of solar energy by the ground and the atmosphere, which takes time to translate into a measurable temperature increase.

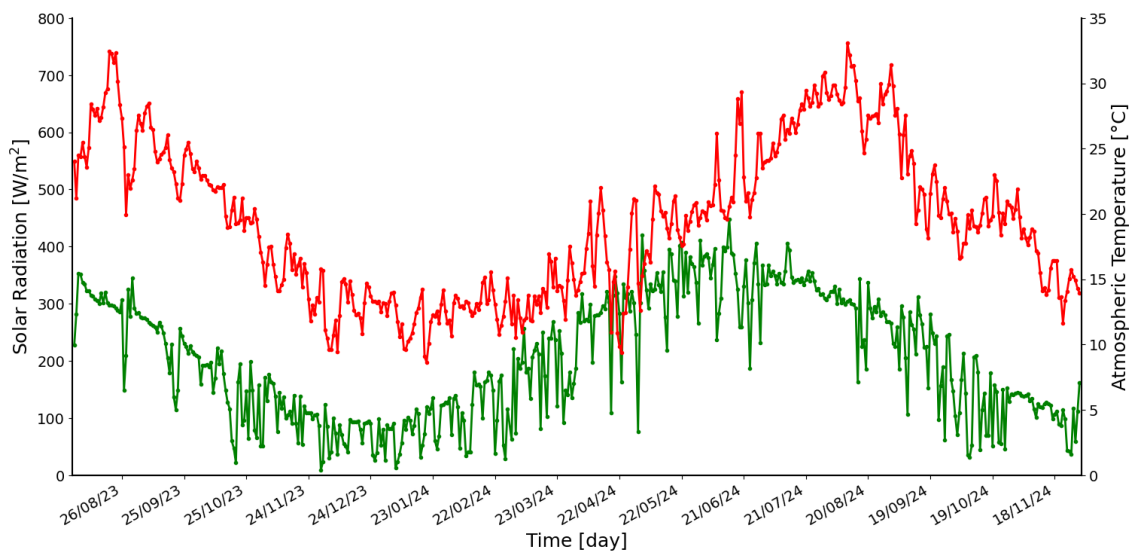


Figure 5.11 - Comparison between solar radiation and atmospheric temperature recorded by the Manarola station.

5.1.2 Hydrological data

In the following sections, the analysis and quality assessment of the hydrological data is presented. The reliability of this data was subsequently compared with the previously analysed meteorological parameters to ascertain the overall consistency.

Experimental Site 846

Soil Moisture

Analysis of the soil moisture data shows a high level of continuity and reliability (Figure 5.12). No significant interruptions or anomalous values were detected, thus providing a solid basis for subsequent hydrological analyses (Figure 5.12). The variations in water content follow a clear seasonal trend, with maximum values typically observed during the autumn and winter months, and minimums recorded in the summer period. The sensors recorded a volumetric water content (VWC) fluctuating between a maximum of 0.33 and a minimum of 0.08 (Table 5.1). The trend in measurements across the sensors is consistent, but with distinct values that reveal a clear hydrological stratification of the soil. It was observed that the water content increases with depth, suggesting that the deeper layers have a greater water storage capacity and lower permeability.

Table 5.1 - Maximum and minimum values of volumetric water content, recorded by the three sensors.

	VWC max	VWC min
SM01	0,27	0,08
SM02	0,29	0,09
SM03	0,33	0,10

Shallow sensors exhibit greater water content variability, being more susceptible to atmospheric interaction, indicating that this soil horizon responds rapidly to precipitation (VWC increase) and evapotranspiration (VWC decrease).

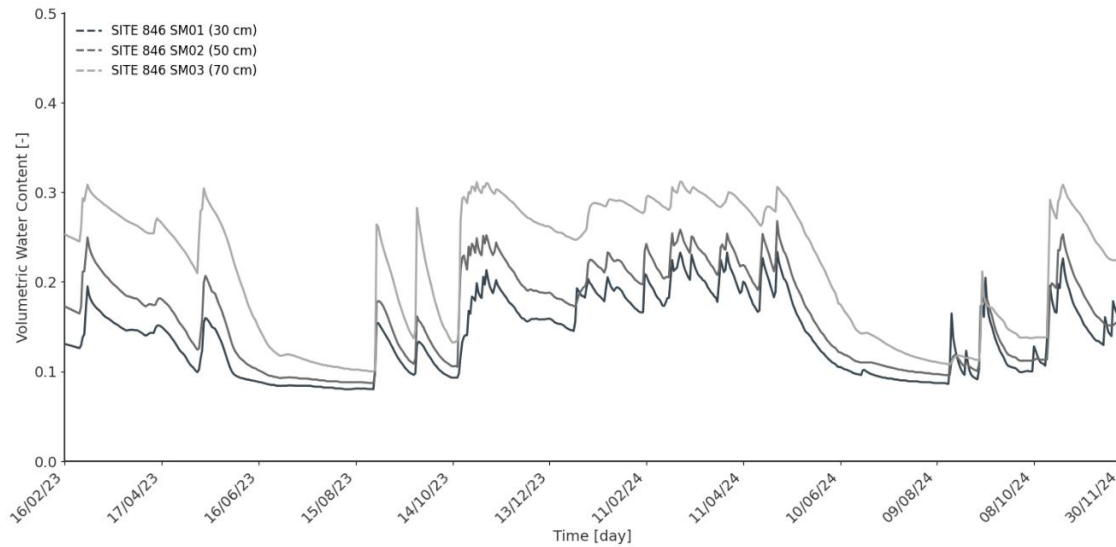


Figure 5.12 - Variations in water content recorded during the monitoring period.

Comparative analysis between rainfall events and VWC, measured at various depths (30, 50, and 70 cm), was aimed at verifying the consistency of the monitoring data and at accurately delineating the dynamics of water infiltration. The comparison revealed a direct and anticipated correlation between precipitation and the subsequent change in soil moisture, thereby confirming the typical infiltration and water retention dynamics characteristic of the site (Figure 5.13).

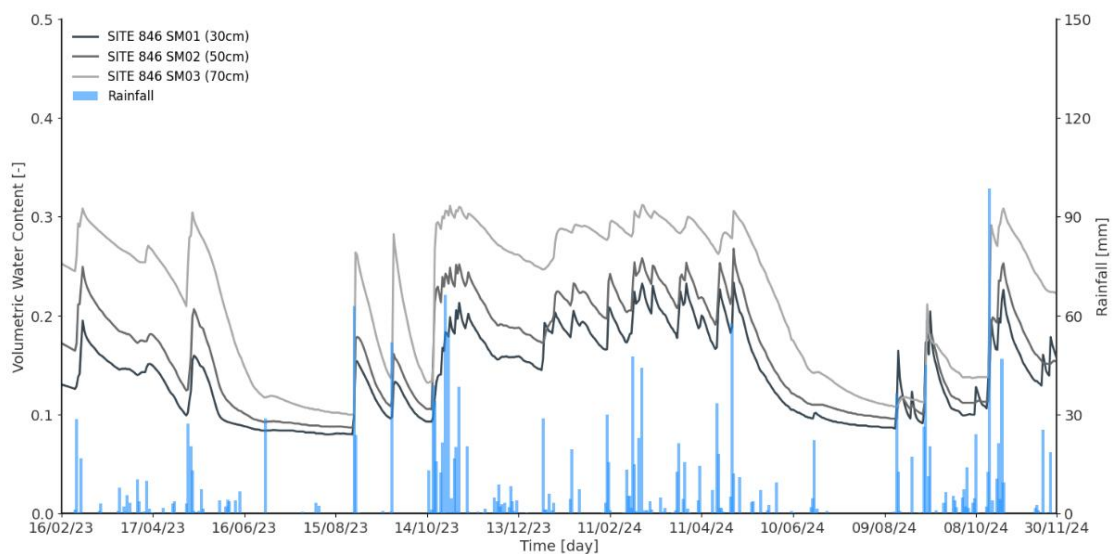


Figure 5.13 - Comparison between the variation in soil water content and precipitation values.

The soil moisture response to rainfall events proved to be almost immediate in the shallow layer (30 cm). Conversely, a marked delay in the change of VWC was observed in the deeper levels

(50 cm and 70 cm), which provides clear evidence of the percolation time required for water to reach these depths. During drying phases, the decrease in water content is both more rapid and more significant in the shallow layer, primarily due to evapotranspiration processes. Conversely, the reduction in water content occurs with a slower progression at greater depths. It is relevant to note that at a depth of 70 cm a higher basal water content compared to the overlying levels was observed. This phenomenon suggests a reduced influence from superficial evaporative processes and, consequently, a greater capacity for water retention at that specific depth.

Matrix potential

The matrix suction data recorded by sensors WP01, WP02, and WP03 at different depths (30, 50, and 70 cm), show good continuity and consistency. The trend of the curves clearly reflects the soil's response to seasonal variations in water conditions, confirming consistency with seasonality. During the 'wetting' phases, the matric potential is less negative (closer to zero), which reflects a high soil moisture content, approaching saturation. In the 'drying' phases, the divergence between the curves increases. In this context, the sensor at the greater depth (WP03 at 70 cm) recorded the most negative potentials. This difference may be attributable to the greater compaction of the soil layer at 70 cm. A more compacted soil is made up of smaller pores, which intensify the adhesive forces between particles and water. Consequently, the dominance of capillary and adhesive forces increases the resistance to water removal, resulting in an increase in the suction value. On average, the maximum suction values (i.e., the most negative values) reached by the soil within the considered depth range are around -2600 kPa.

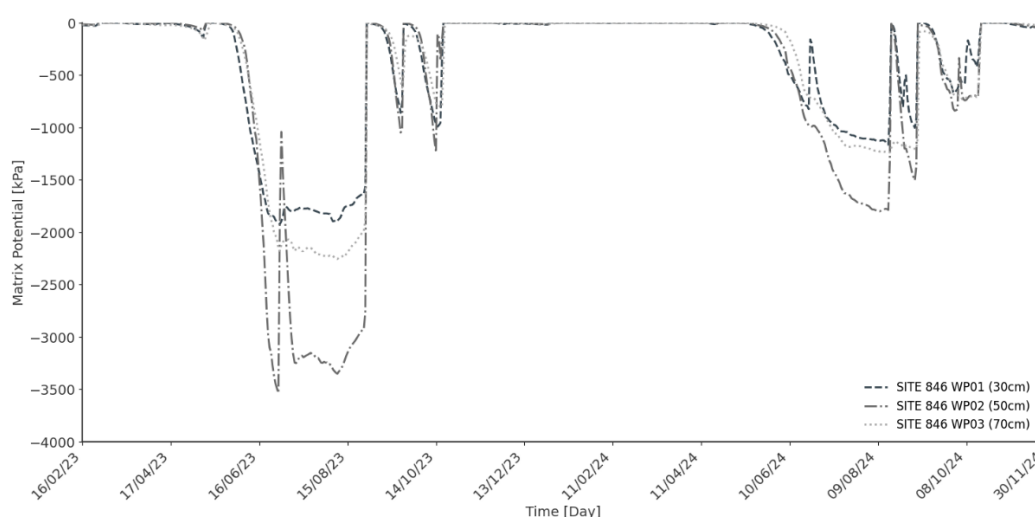


Figure 5.14 - Variations in matrix potential recorded during the monitoring period.

The previously validated volumetric water content data were correlated with the matrix suction values in order to verify their reliability (Figure 5.15).

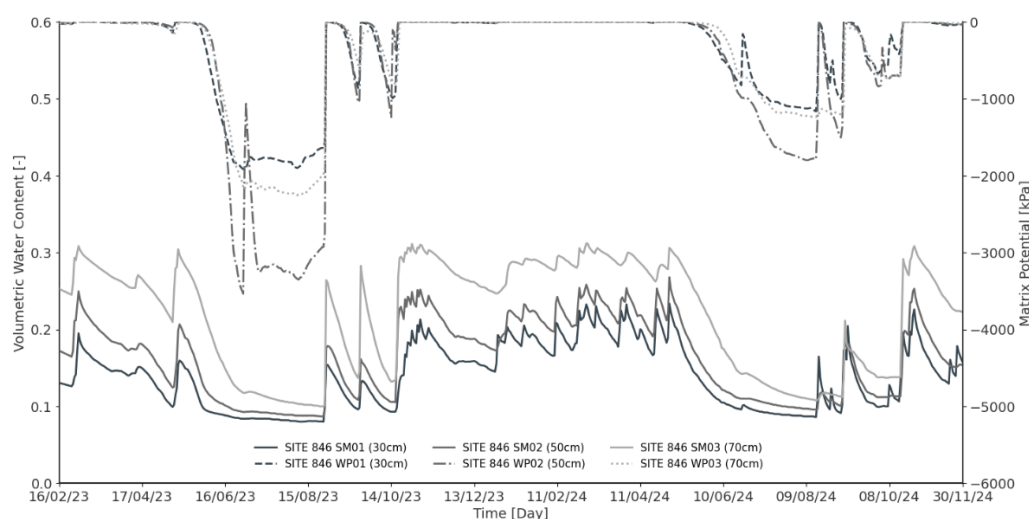


Figure 5.15 - Comparison between the variation in soil water content and matrix potential.

The correlation analysis between VWC and matric suction resulted in data reliability, systematically consistent with the fundamental principle of the Water Retention Curve (WRC). The comparison demonstrated a significantly consistent inverse relationship: as soil water increases, i.e., during imbibition phases, matric suction progressively decreases until it reaches zero under saturated conditions. This is because the disappearance of water menisci eliminates capillary tension and apparent cohesion. Conversely, during drying periods caused by evapotranspiration, the decrease in water leads to a marked increase in suction. This occurs because the residual water is held more strongly by intense adhesive forces and surface tension within the smallest pores, requiring progressively greater effort for extraction.

This consistency observed across all measuring depths constitutes a remarkable cross-validation that reinforces the reliability of data acquired from both types of sensors. The short temporal lag observed between the measurements is attributable only to minor factors, such as the inevitable small differences in sensor placement within the soil or the inherent responses due to the specific technologies and operational physical principles of each instrument.

Experimental Site 915

Soil Moisture

At site 915 VWC data series is continuous and free from interruptions or anomalous values, confirming the reliability and stability of the measurement system (Figure 5.16).

Data from the sensors indicate a lower water storage capacity compared to the previous site. The VWC shows a narrower oscillation range, with values ranging from a maximum of approximately 0.28 to a minimum of 0.1 (Table 5.2). This reduced water retention capacity may be correlated to a coarser grain size.

Table 5.2 - Maximum and minimum values of VWC.

	VWC max	VWC min
SM01	0,30	0,086
SM02	0,25	0,103
SM03	0,28	0,128

The VWC values varies with depth (Figure 5.16). The deepest sensor (SM03 at 50 cm) recorded, on average, higher moisture values, especially during the summer months, while the shallowest one (SM01 at 20 cm), is more affected by interactions with the atmosphere, showing more pronounced oscillations and a lower water content.

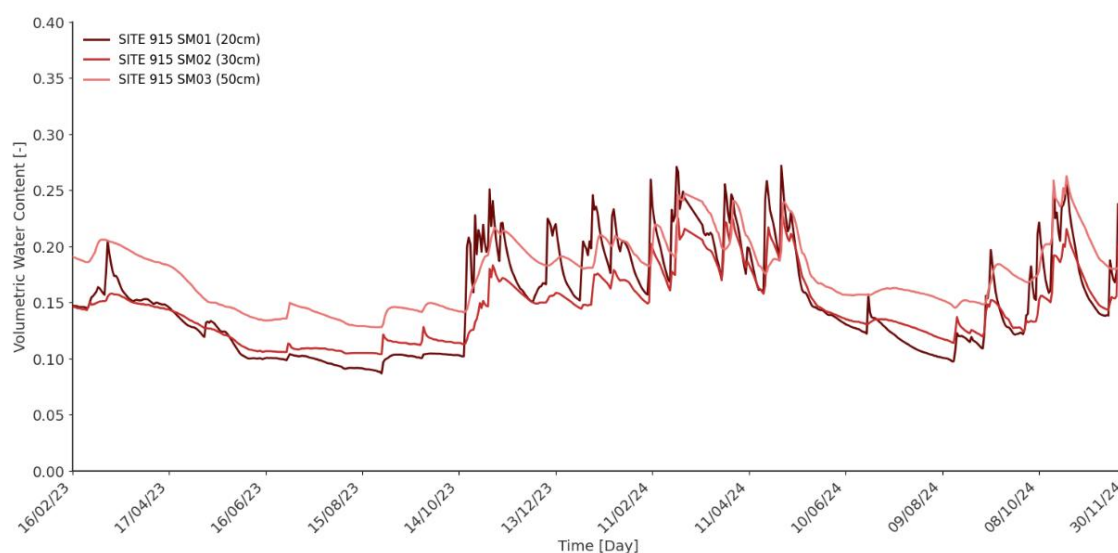


Figure 5.16 - Variations in water content recorded during the monitoring period.

Data are consistent with seasonal cycles: higher VWC values are observed in the rainiest months (October-April) while and a progressive decrease in the summer months (July-September) due to evapotranspiration was observed. During wetting cycles, the water content measured by sensors at different depths is very similar. In the drying period, a divergent behaviour is observed: the superficial sensors show a more rapid and pronounced drop in water content. Conversely, the deepest sensor maintains a higher water content and a nearly constant

variation. This phenomenon is correlated with the interaction with the atmosphere: processes such as evapotranspiration, which cause a rapid loss of moisture in the upper layers, are attenuated or almost null at greater depths.

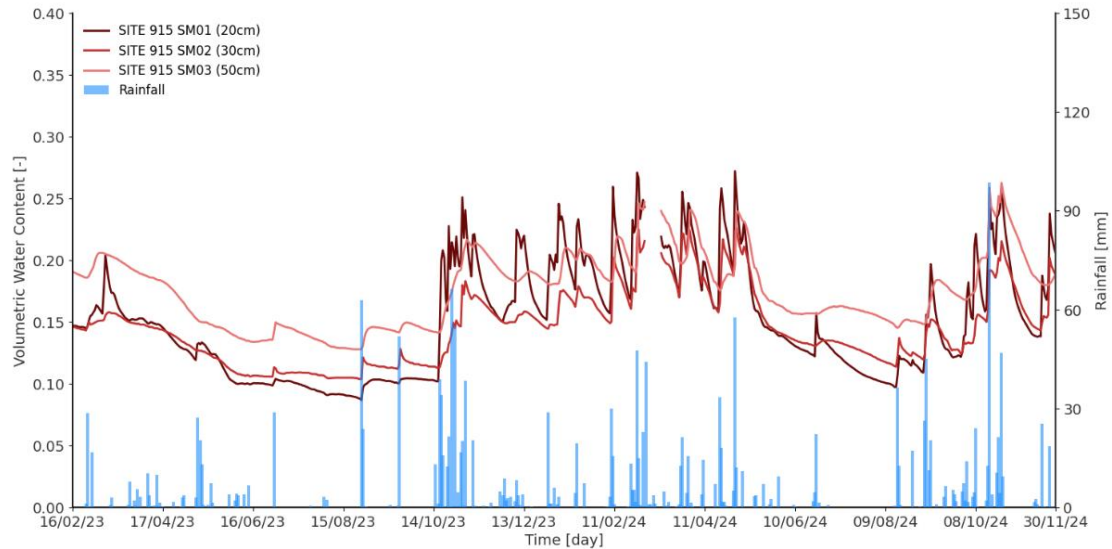


Figure 5.17 - Comparison between the variation in soil water content and precipitation values recorded by the Manarola station.

The correlation between rainfall events and VWC is clear and direct: each significant precipitation event induces an increase in VWC due to infiltration and pore saturation. This response is more rapid and pronounced in the shallow layers (20 and 30 cm), whereas the deepest sensor (50 cm) exhibits an evident delay and reduced intensity, consistent with the expected percolation time.

Matrix suction

Data from the suction instruments show a continuous trend, with no interruptions or anomalies. The overall pattern reflects seasonal cycles: during the summer months (June to September), suction values reach high negative pore water pressures (Figure 5.18). Conversely, in the winter months, characterized by higher rainfall levels, the recorded suction values are very low, close to zero. Therefore, within the monitored depth range, measurements fluctuate from values near zero in winter to mean negative suction values of around -3000 kPa.

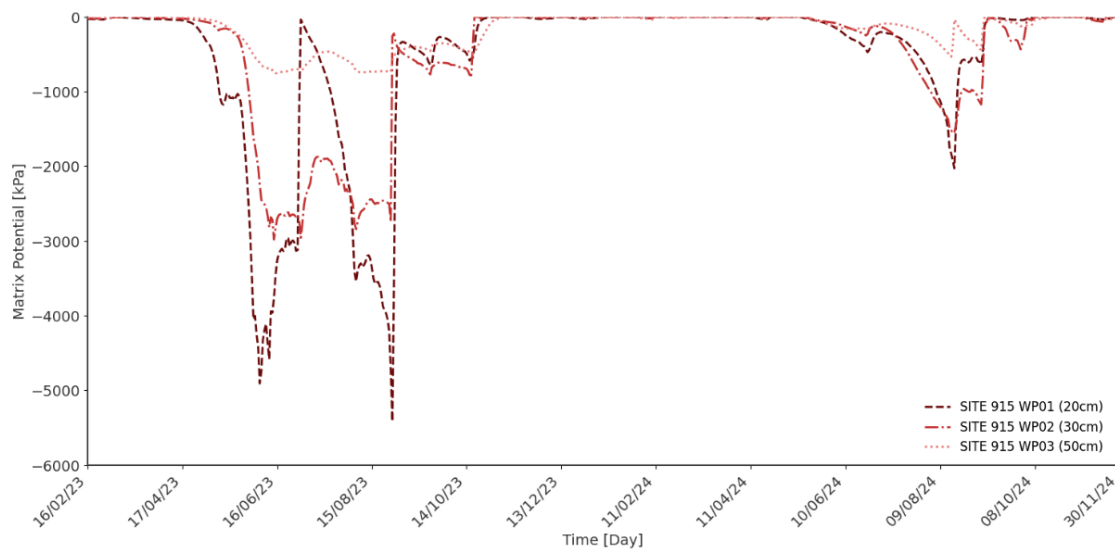


Figure 5.18 - Variations in matrix potential recorded during the monitoring period.

A marked vertical gradient in matric suction can be observed, dominated by the interaction between the atmosphere and the ecosystem. Shallow sensors (20–30 cm) recorded significant negative values (up to -5000 kPa) and rapid fluctuations. This is probably due to the maximal influence of evapotranspiration combined with intense water extraction operated by high root concentrations, indicating a condition of severe plant water stress. Conversely, the deepest sensor (50 cm), located near the substratum and characterised by a low root density, showed lower values (maximum -1000 kPa) and a dampened trend, with variations depending almost exclusively on slow percolation.

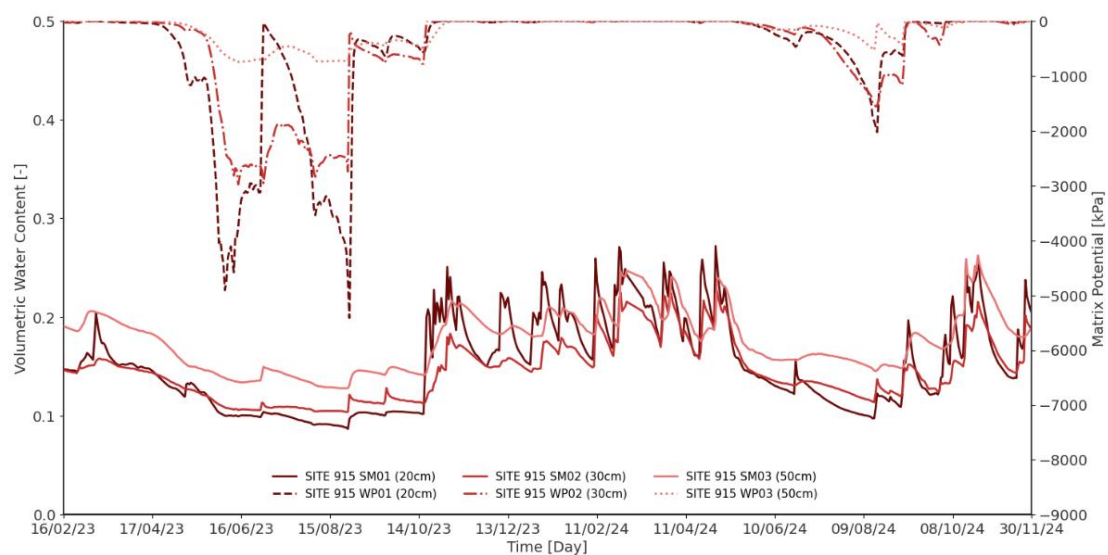


Figure 5.19 - Comparison between the variation in soil water content and variation of matrix potential.

A pronounced inverse correlation between VWC and soil suction was found (Figure 5.19): a reduction in VWC corresponds directly to an increase in the soil retentive force. This relationship is more clearly noted in the shallow layers (20–30 cm depth). During drying periods, particularly over the summer months, a rapid and marked decline in VWC occurred. This, in turn, resulted in an abrupt increase in suction. This behaviour is indicative of the fact that the combined loss of water via evapotranspiration and root uptake induced the soil matrix to retain firmly the remaining moisture.

In contrast, the deeper layer (50 cm depth) exhibited a far more attenuated and stable dynamic. VWC at this depth remained at higher values with minimal fluctuation. Consequently, the matric potential showed limited variation, with less pronounced suction peaks and values that rarely drop below. This dampened trend may be attributable to the depth, being less susceptible to superficial climatic factors and to root activity.

Furthermore, the period between October 2023 and April 2024, characterised by more frequent and significant rainfall events, led to a marked increase in VWC. This rise had direct implications for suction, which drastically decreased, approaching levels close to zero, thereby indicating that the soil was nearly saturated.

Experimental Site 850

Soil Moisture

Monitoring data for volumetric water content at site 850 show high continuity, and no periods of signal interruption or malfunction, nor any values indicating operational anomalies occurred. The trend of VWC followed seasonal cycles, reaching values close to saturation in the autumn and spring months (October 2023 - April 2024) (Figure 5.20). A period of prolonged drought, where VWC reached a constant minimum value was identified in the months from June to August 2024, followed by an increase in water content during the autumn months.

At this site, the highest recorded VWC in both wetting and drying phases were recorded. During the wetting period, it reached maximum values of 0.46, while in the drying periods, the value was around 0.10 (Table 5.3).

Table 5.3 - Maximum and minimum values of volumetric water content.

	VWC max	VWC min
SM01	0,42	0,12
SM02	0,46	0,12
SM03	0,42	0,10

The water storage capacity at Site 850 may be basically governed by two key factors: high porosity and high organic matter content. A high total porosity, quantified as high as 50% at Site 850, can be correlated to a greater volume of available pore space for water storage. Soil made up of high organic matter can have a remarkable ability to absorb and retain water (Aspetti, 2006).

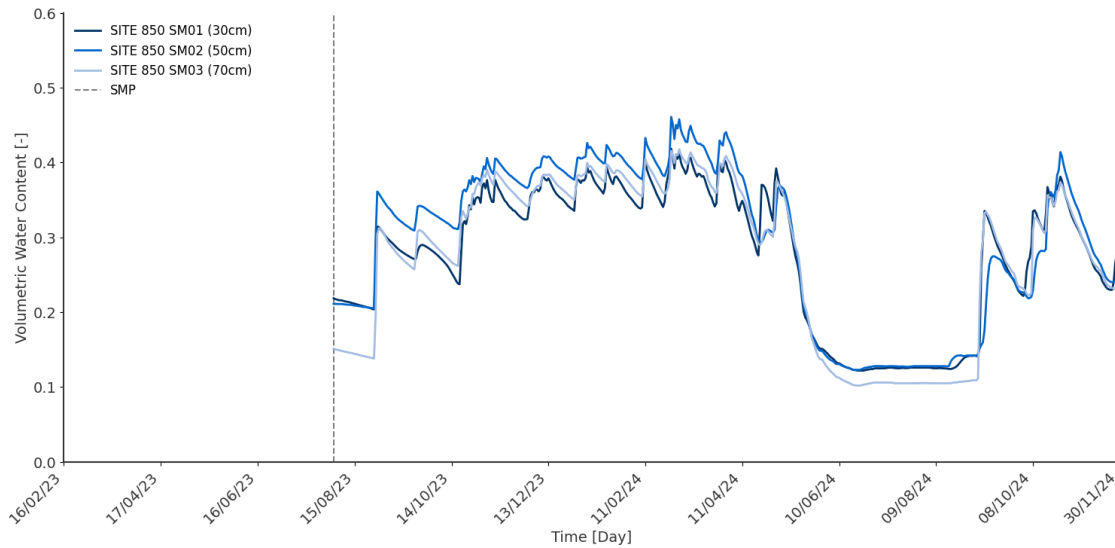


Figure 5.20 - Variations in water content recorded during the monitoring period (the dashed line indicates the beginning of the monitoring period (Start Monitoring Point – SMP) relative to the other sites).

During the wetting process, deeper VWC sensors exhibited a similar behaviour to those near the surface. However, during the drying period, these sensors registered lower VWC compared to the shallow ones. This discrepancy can be explained by analysing the relationship between VWC and precipitation (Figure 6.21).

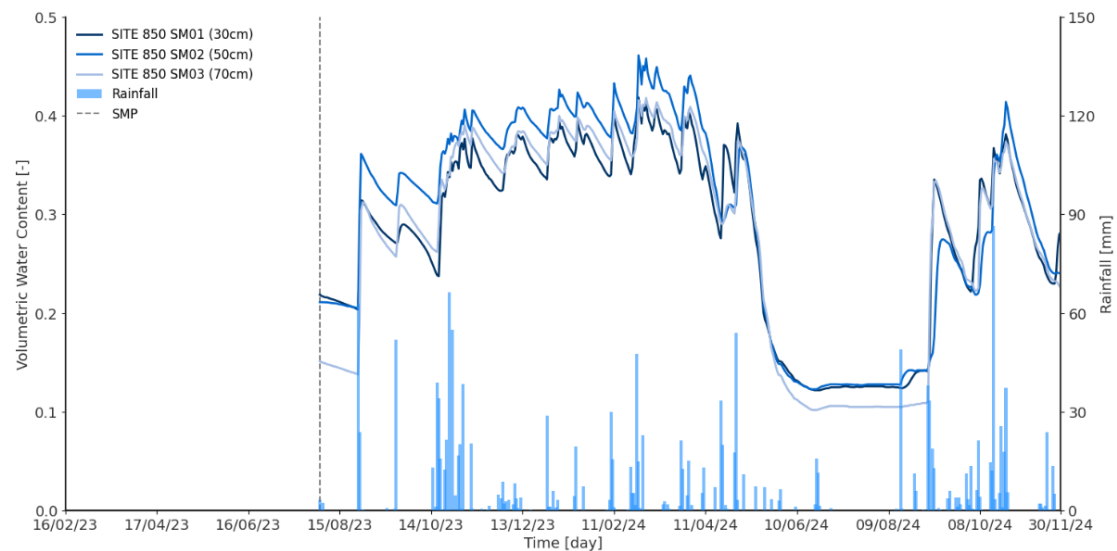


Figure 5.21 - Comparison between the variation in soil water content and precipitation values (the dashed line indicates the beginning of the monitoring period (Start Monitoring Point – SMP) relative to the other sites).

During the summer period (May-September), the combination of low rainfall and high evapotranspiration maintained VWC near residual levels. Light rainfall is largely intercepted and retained by plant roots within the top 20–30 cm, restricting water availability to the surface layers (30–50 cm). Summer precipitation events, such as the 43 mm recorded on August 17, 2024, only partially rehydrated the surface. Crucially, these events were not sufficient to reach or replenish the whole soil layer, which remained dry. Only prolonged and continuous rainfall allowed water to percolate to depth, leading to a significant increase in VWC to values approaching saturation at 70 cm below ground level. This highlighted that only intense and prolonged precipitation events could recharge the deep soil layers, which are essential for mitigating drought conditions.

Matrix potential

Soil matric potential monitoring showed data continuity and reliability, with no significant anomalies. The analysis of suction potential revealed two distinct dynamics, which are closely correlated with seasonal variations.

During months characterized by abundant and frequent rainfall, the soil remains in saturated or nearly saturated conditions. Consequently, the recorded suction values were very low, approaching zero. In contrast, during the summer period, the soil underwent rapid desaturation, causing extremely negative suction values, approximately -1700 kPa.

Unlike other sites, the sensors at site 850 exhibited an almost identical trend regardless of installation depth, even during the drying phase. This phenomenon suggests considerable soil homogeneity, indicating that the suction potential is uniformly distributed throughout the entire profile.

After the summer drying period, the soil's response to precipitation events showed a differentiated behaviour based on depth. The shallow sensor reacted almost immediately to the increase in water content, absorbing the water instantaneously. The sensors placed at greater depths, however, recorded the increase with a certain delay. This delay is attributable to the time needed for water to infiltrate and percolate through the soil profile, especially after a long drying period that has brought suction values to minimal levels.

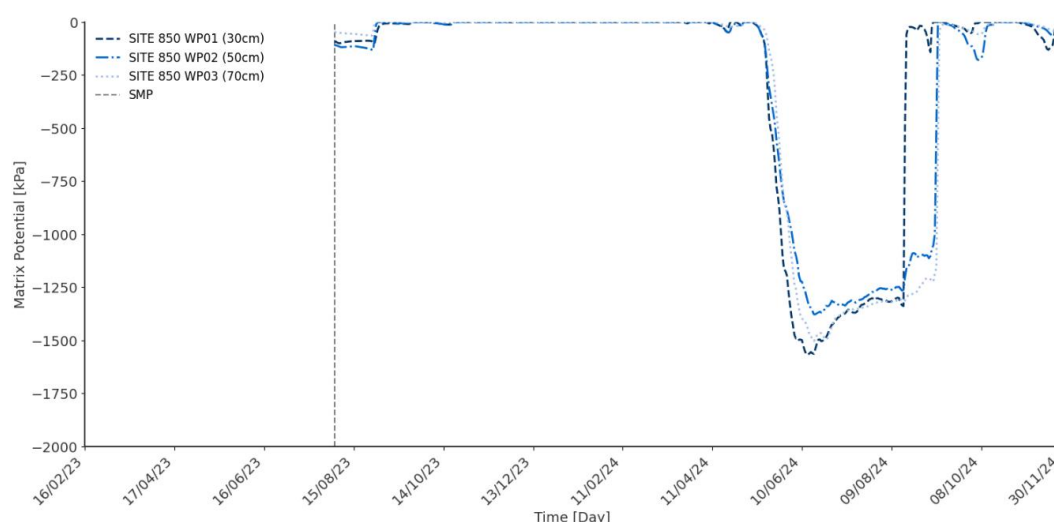


Figure 5.22 - Variations in matrix potential recorded during the monitoring period (the dashed line indicates the beginning of the monitoring period (Start Monitoring Point – SMP) relative to the other sites).

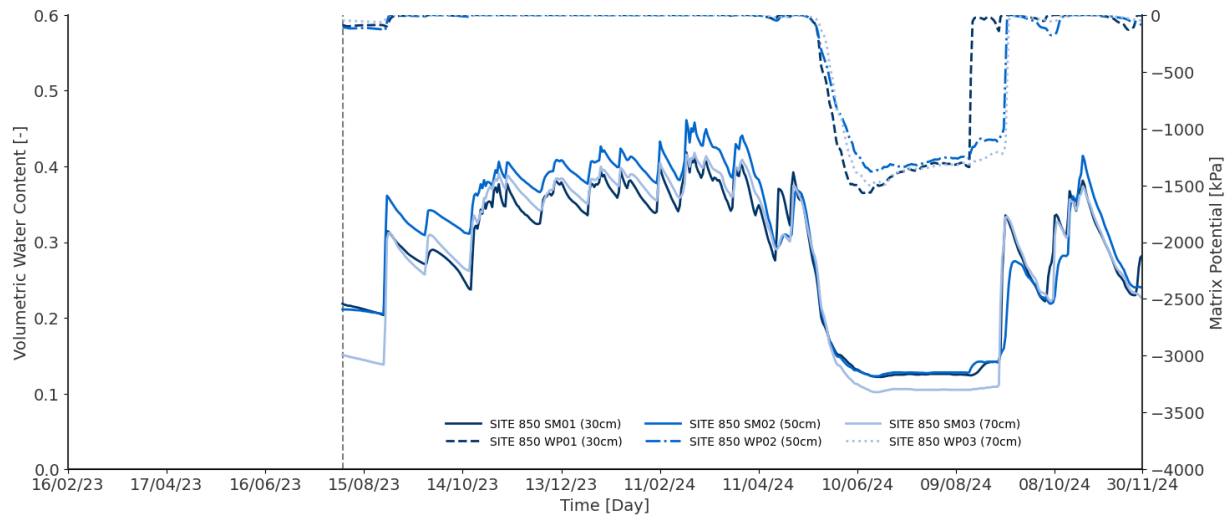


Figure 5.23 - Comparison between the variation in soil water content and variation of matrix potential (the dashed line indicates the beginning of the monitoring period (Start Monitoring Point – SMP) relative to the other sites).

The data analysis revealed a clear and direct inverse correlation between (VWC) and matrix potential (Figure 5.23).

5.1.3 Total load cell monitoring data

The monitoring of total pressures has revealed a remarkable data continuity and consistency. Despite this observation, a comparison between the precipitation trend and the total pressure recorded by the cells indicates a time-lagged cell response with respect to the rainfall event (Figure 5.24).

This is observed because, during periods of high precipitation, the cells are expected to register elevated total pressure values. This pressure results from the thrust exerted by the soil and water against the back face of the wall. However, this correspondence is not immediate but rather appears time lagged. A similar, but inverse behaviour occurs during drying.

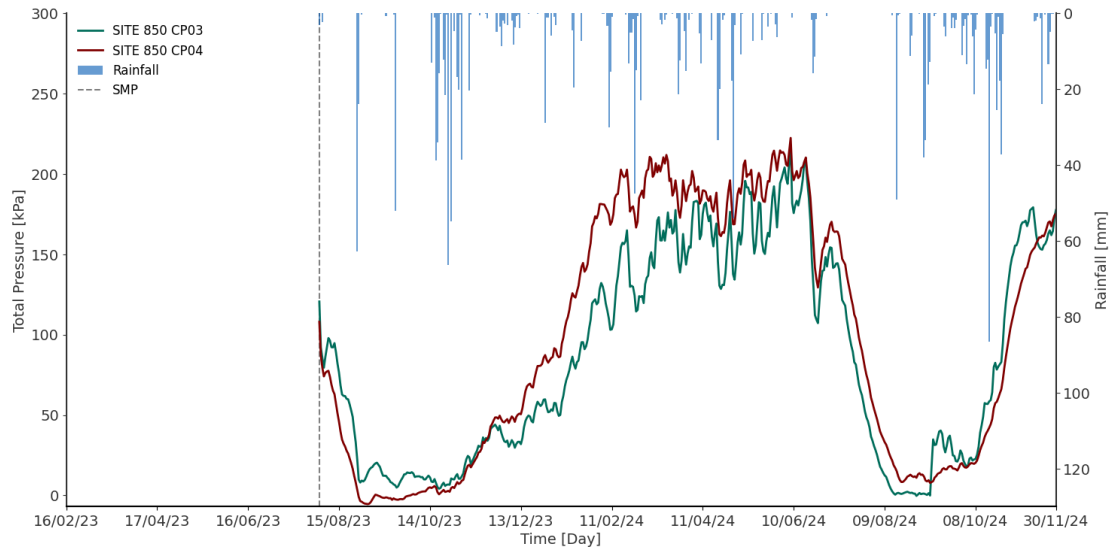


Figure 5.24 - Comparison between rainfall and variations in total pressure recorded during the monitoring period (CP03 and CP04: load cells deployed in vertical position; the dashed line indicates the beginning of the monitoring period (Start Monitoring Point – SMP) relative to the other sites).

Furthermore, the absolute values recorded by the pressure cells are significantly out of compared to the theoretical values expected for the current slope geometry.

Based on the available information, the theoretical horizontal stress for a backfill layer approximately 2 meters thick, under a critical condition with the presence of water, is about 12.24 kN/m². According to the installation depth, the measuring sensors should measure values of approximately 5.12 kN/m² and 9.8 kN/m², respectively. These data are consistent with the total horizontal stress values reported in the literature, such as by Preti et al. (2014, 2018b), which found similar values on terraced areas with comparable soil thicknesses.

Therefore, the significant discrepancy between the values measured by the cells (which reach peaks of approximately 200 kN/m²) and the calculated theoretical values suggests that the data are unsuitable for quantitative analysis. This discrepancy is attributable to the use of a pressure cell with an excessively wide measurement range (full scale) relative to the actual total pressure values. The sensor's high full scale may introduce a constant absolute error which, when compared to the much lower pressure values encountered in the field, can significantly affect measurement accuracy and reliability. To analyse the issue concerning the lateral pressure measurements, which were found to be excessively high and deviating significantly from theoretical values, the raw current values (in mA) registered directly by the cell prior to conversion into kPa were checked. These values were found to be reliable based on the

calibration graphs provided by the manufacturer (Figure 3.15). It was therefore established that the error could not be correlated with the raw data recorded by the cell.

Furthermore, it was not possible to independently calibrate the pressure cells within a barometric chamber to generate calibration curves consistent with the monitored problem, and this represents a limitation for the quantitative analysis of the data. Corrective calibration curves, referenced against the theoretical value, could not be created because the cells had already been installed inside the wall structure.

Consequently, in this work, the field data registered by the pressure cells were utilized only in qualitative terms.

Consequently, the acquired data were for analysing the relative variations and trends of the total pressures. To validate the qualitative data trends, a comparative analysis with suction and VWC measurements was made (Figure 5.25 and 5.26).

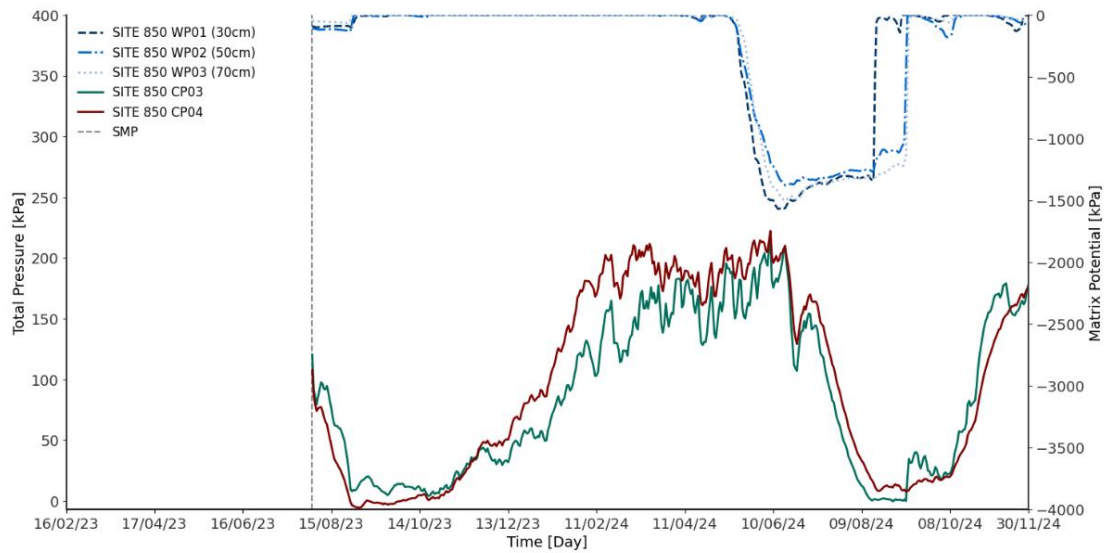


Figure 5.25 - Comparison between the variation in total pressure and variation of matrix potential (CP03 and CP04: load cells deployed in vertical position; the dashed line indicates the beginning of the monitoring period (Start Monitoring Period - SMP) relative to the other sites.

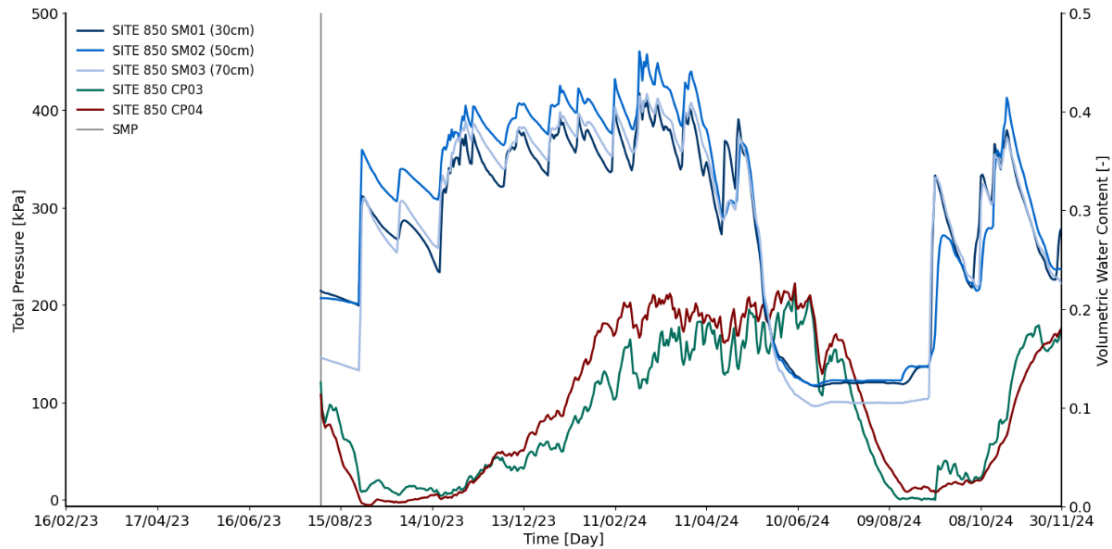


Figure 5.26 - Comparison between the variation in water content and variation of matrix potential (CP03 and CP04: load cells deployed in vertical position; the dashed SMP (Start Monitoring Period) line indicates the beginning of the monitoring period (Start Monitoring Period - SMP) at site 850 relative to the other sites.

The analysis revealed a clear correlation between an increase in VWC and the response of the various sensors. As humidity rises, a corresponding decrease in suction is observed, which reflects a reduction in capillary forces within the soil. Similarly, total pressure cells also registered an increase in horizontal stress as a direct result of the elevated water content.

Although total pressure cell data exhibited an oscillatory trend that mirrored the water content, a significant time delay has been observed between the two measurements.

The time lag observed between the increase in Volumetric Water Content (VWC) and the corresponding registration of an increase in horizontal stress by the total pressure cells was hypothesized to be a phenomenon of delayed mechanical stress transfer. The increase in VWC is a hydraulic change within the soil matrix (specifically, a decrease in suction), whereas the pressure cell measures the mechanical effect of this variation. This temporal offset occurs because the hydraulic change must first translate into a new effective stress configuration within the soil, and subsequently, this mechanical stress must be transferred to the soil-structure interface.

5.1.4 Determination of the temporal domain

Following the data quality assessment, a comparison of water content graphs was conducted across the three investigation sites in order to isolate a common monitoring period characterised

by data completeness and consistency. This selection is crucial for defining a representative time interval encompassing a complete hydrological cycle (wetting-drying cycle).

Based on a comparative analysis of the validated VWC graphs at various depths, a notable similarity between the recorded values has emerged. Consequently, to optimise the analysis and modelling, an exclusive selection of data from the VWC (and Matric Potential) sensor positioned at the intermediate depth was carried out. These data were deemed sufficiently representative of the hydrological conditions of the entire soil profile (Figure 5.27). The same methodology was applied to the matric potential data.

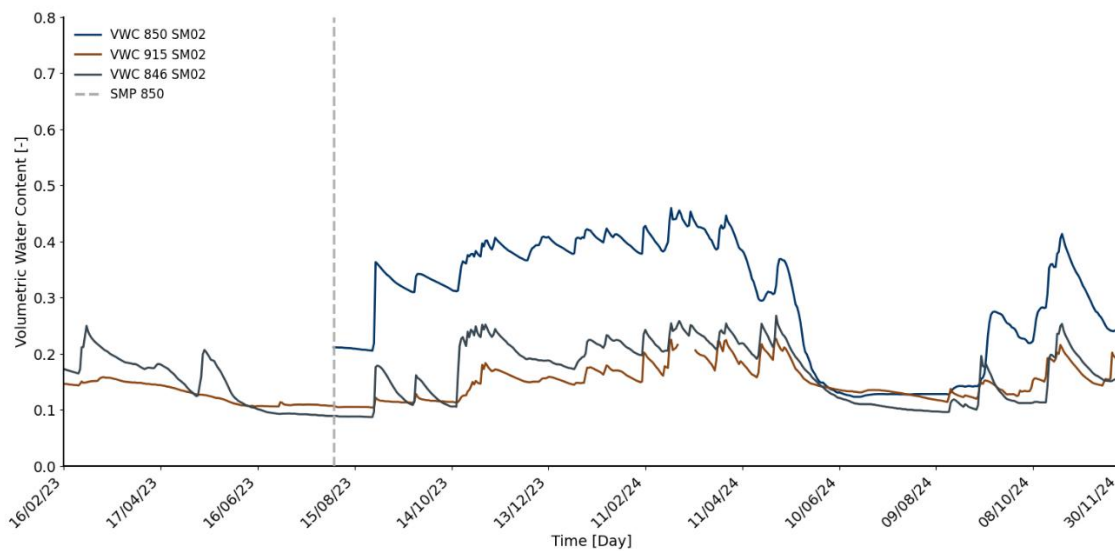


Figure 5.27 - Comparison of the variations in water content in the intermediate sensor at the three experimental sites (the dashed line indicates the beginning of the monitoring period (Start Monitoring Period- SMP) at site 850.

The comparative analysis showed that Site 850 has the highest values of volumetric water content (VWC), ranging from 0.12 to 0.46. These results indicate a greater water storage capacity than Sites 846 and 915. This significant difference is mainly attributable to two determining factors: the physical properties of the soil and the type of vegetation. Total porosity is an essential parameter for water retention. The data collected show that porosity is higher at Sites 850 (0.51) and 846 (0.46) than at Site 915 (0.43), supporting a clear positive correlation with VWC. The higher porosity at Site 850 is most likely related to the engineering-geological features of the soil forming the terrace embankment. Indeed, unlike at sites 846 and 915, where hydrological sensors were installed into undisturbed material, at Site 850 the soil was intensely reworked due to the backfill construction activities. This result in poor soil compaction, likely leading to higher total porosity than undisturbed soils at sites 915 and 846. In addition, the

different vegetation cover influenced not only the VWC, through evapotranspiration processes, but also the accumulation of organic matter. This interaction is widely confirmed in the scientific literature (Zhou et al., 2012; Taguas et al., 2015; Laganière et al., 2022; Šimanský et al., 2023).

Site 850 (Wild Grass) is the most efficient in accumulating organic matter (OM) thanks to two synergistic factors. First, grasses develop a dense, shallow fibrous root system characterised by high and continuous turnover, which constantly releases OM directly into the soil matrix. Second, the absence of mechanical tillage prevents oxygenation and the consequent acceleration of microbial decomposition and mineralisation of OM. In contrast, Site 915 (Vineyard) has a lower OM content due to agronomic practices. Tillage induces aeration of the surface layers, significantly stimulating microbial activity and, consequently, rapid decomposition and mineralisation of OM. Finally, Site 846 (Shrubs and Scrub) is in an intermediate position. Although it benefits from the absence of mechanical tillage (which preserves OM), total accumulation is limited by the intrinsic characteristics of shrub vegetation. Shrubs develop more lignified and deeper root systems with a much slower turnover than grass. Furthermore, the supply of OM is primarily surface necromass; although this contributes to humus, its decomposition and incorporation into the surface layers of the soil is less immediate and widespread than the constant root release of grasses (Zhou et al., 2012).

The comparative analysis of monitoring data acquired at the three experimental sites allowed for the identification of a complete hydrological cycle. This cycle clearly includes the drying phase (characterised by a progressive decrease in water content) and the subsequent wetting (or imbibition) phase (during which the water content approaches saturation values). The monitoring period selected for this purpose extends from May 02, 2024, to September 15, 2024.

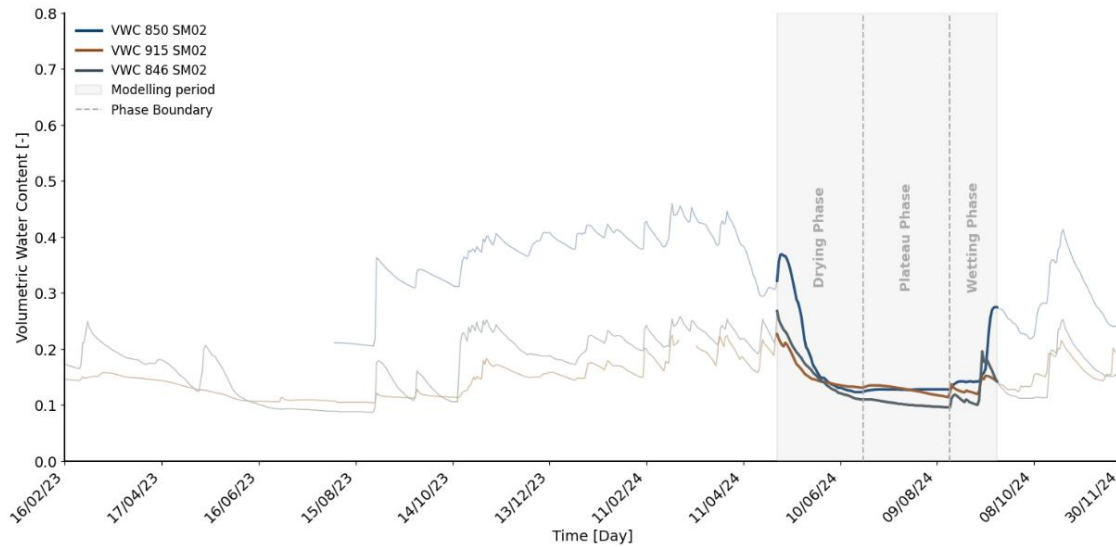


Figure 5.28 - Time series of VWC recorded at the three sites (850, 915, 846). The shaded area highlights the modelling period (02/05/2024 – 15/09/2024), which is further delineated into the Drying, Plateau, and Wetting phases by the dashed vertical lines and grey labels.

The observed time window was selected with the primary objective of preserving the maximum integrity and continuity of the dataset, ensuring the uninterrupted acquisition of fundamental hydraulic parameters (Figure 5.29). A crucial criterion for this choice depends on the capture of the transient water dynamics, which include the following phases:

- **Drying Phase** (May 02 – June 25, 2024): progressive loss of soil moisture and increase in soil suction.
- **Plateau Period** (June 25 – August 17, 2024): the volumetric water content is maintained at constant values, in the absence of precipitation, and with a likely marked reduction in evapotranspiration rates, as can be inferred from the graphical trend.
- **Wetting Phase** (August 17 – September 15, 2024): increase in soil moisture and decrease in suction values approaching zero.

The observation of this sequence of phenomena clearly outlines a hydraulic hysteresis and is of fundamental importance for the empirical determination of the WRC.

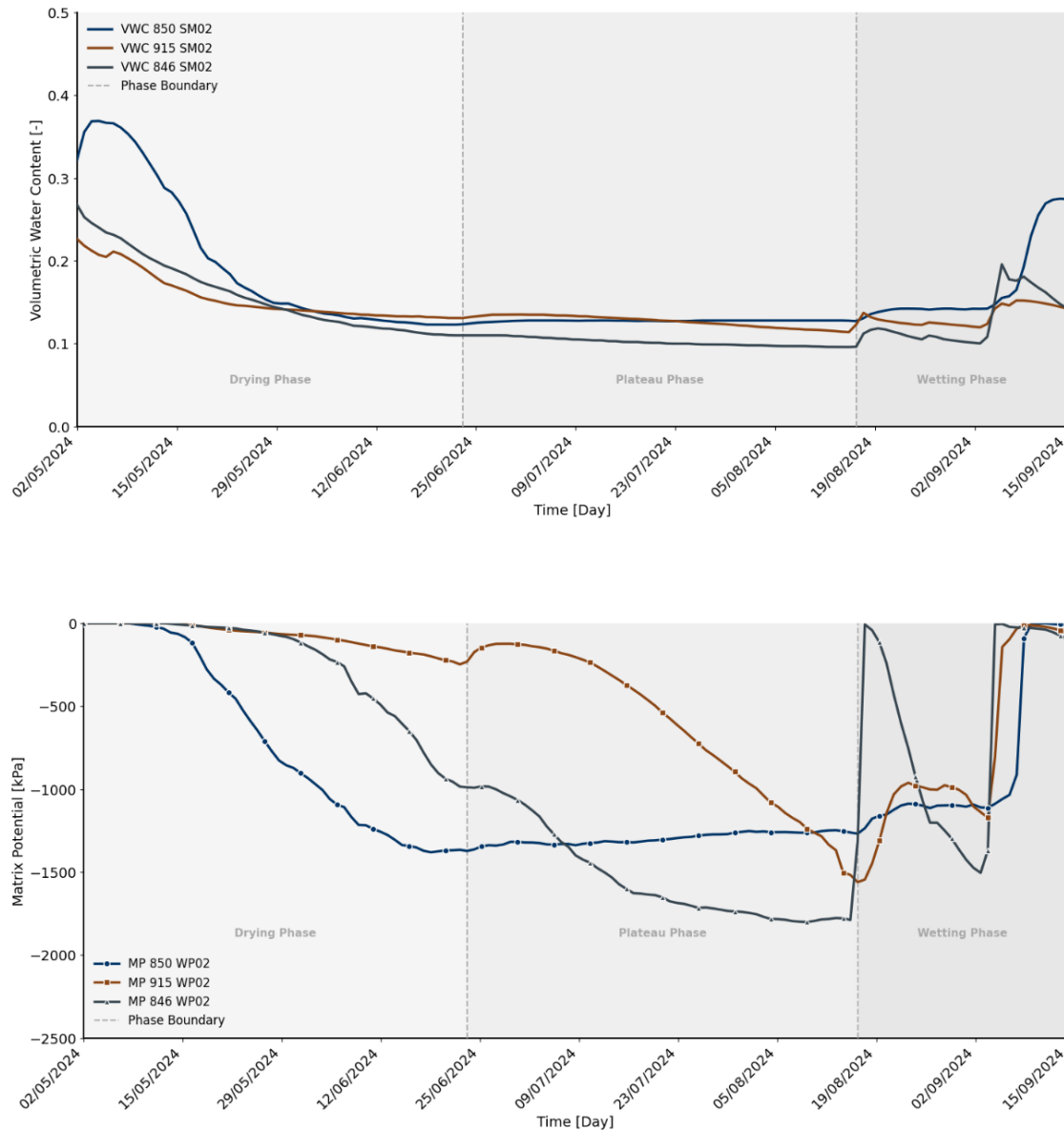


Figure 5.29 - Selected monitoring period for analysis in terms of water content and matrix potential.

5.2 HYDROLOGICAL MODEL DEVELOPMENT

Based on the information pertaining to the selected period, site-specific WRCs were reconstructed. From these curves, the fundamental hydrological parameters were derived.

5.2.1 Intrinsic soil hydraulic properties determination

Figure 5.30 illustrates the temporal evolution of the soil water content and the suction for the three experimental sites over the analysed hydrological period. Examination of the data reveals a distinct inverse proportionality between these variables: a decrease in suction leads to a corresponding increase in water content, and vice versa. This mirrored dynamic reflects the

dynamic hydraulic equilibrium between the water availability within the soil matrix and the matrix retention force.

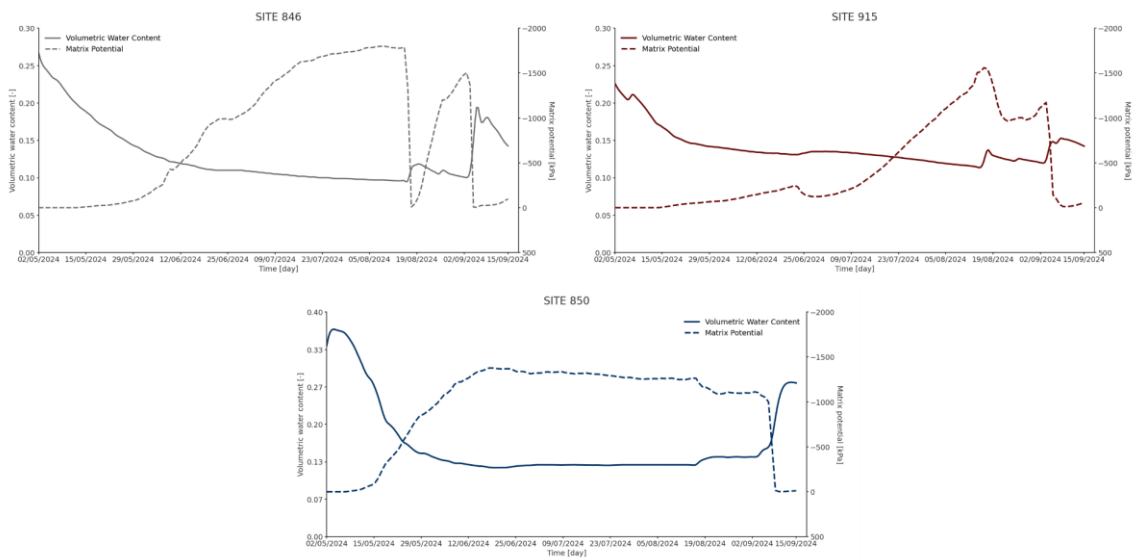


Figure 5.30 - Trends of the variation in water content and suction over the selected monitoring period.

Intrinsic soil hydraulic properties: WRC

The direct relationship between suction and water content provides a discrete description of the behaviour of these two parameters for the different experimental sites (Figure 5.31).

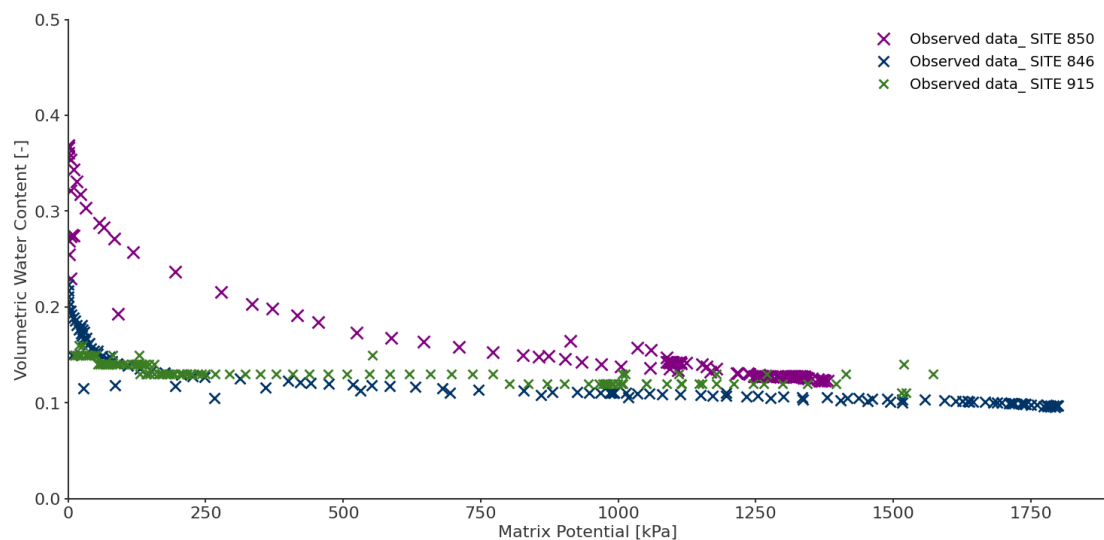


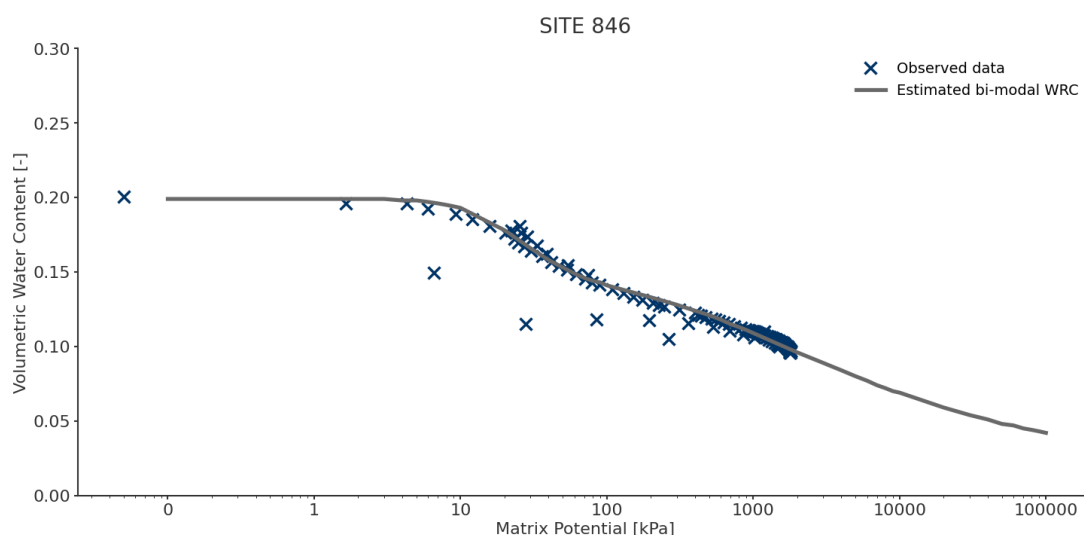
Figure 5.31 - Relationship between water content and suction.

Based on this discrete relationship, the parameters for the van Genuchten model were identified and defined (Table 5.4). Given the dual-porosity nature of the soils at sites 846 and 915, it was necessary to employ the bimodal van Genuchten model (Paragraph 3.3.1.1).

Table 5.4 - Parameters of van Genuchten model.

	van Genuchten parameters								
	θ_{s1}	θ_r	α_1	n_1	m_1	θ_{s2}	α_2	n_2	m_2
	(-)	(-)	(kPa ⁻¹)	(-)	(-)	(-)	(kPa ⁻¹)	(-)	(-)
SITE 846	0,2	0	0,05	2,4	0,58	0,14	0,0024	1,22	0,18
SITE 915	0,16	0	0,028	2,8	0,64	0,13	0,00056	1,36	0,26
SITE 850	0,36	0	0,03	1,28	0,22	/	/	/	/

The van Genuchten model parameters were manually calibrated using a parametric approach that combined graphical analysis with trial-and-error. This procedure identified the best-fitting parameters to define the non-linear mathematical relationship between soil volumetric water content and matric potential (Figure 5.32).



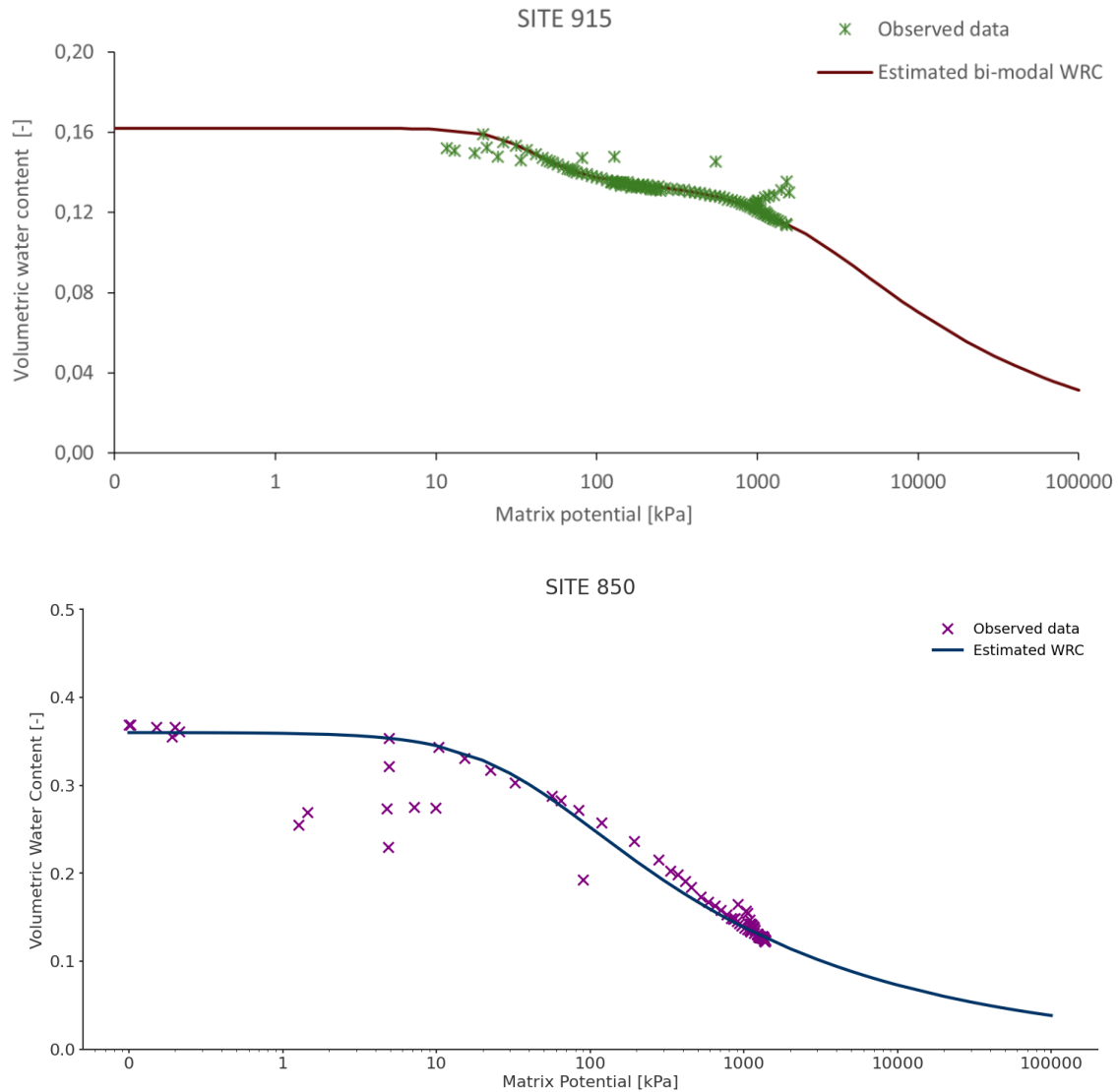


Figure 5.32 - Best fitting between observed data and the van Genuchten's model.

The parameters used to estimate the Water Retention Curve (WRC) are fundamental for the determination of other hydraulic properties, such as the degree of saturation and saturated permeability.

Intrinsic soil hydraulic properties: degree of saturation

Figure 5.33 compares the relationship between saturation degree and matric suction obtained using the empirical van Genuchten and Kozeny-Carman formulations.

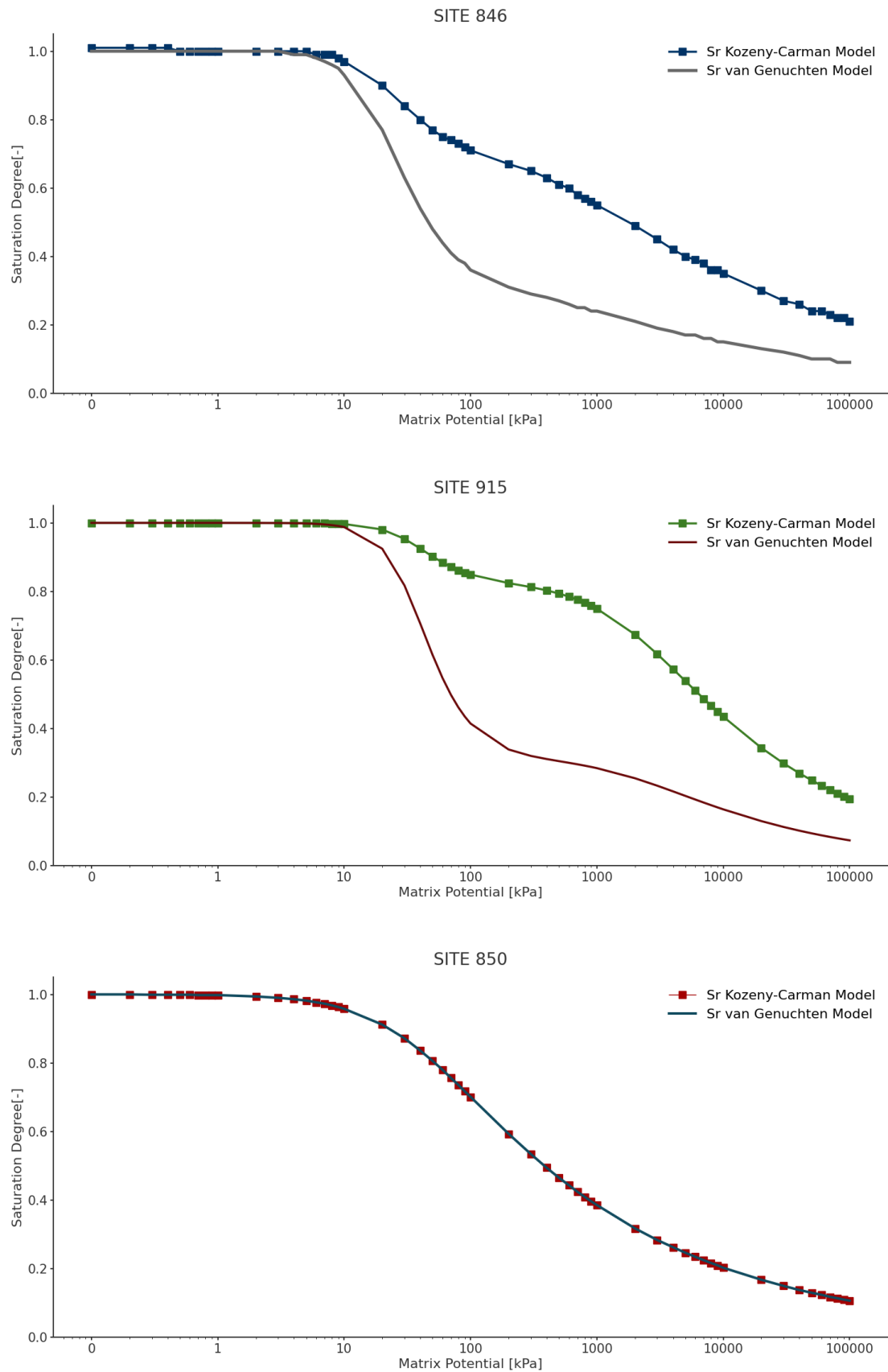


Figure 5.33 - The effective degree of saturation was calculated using two distinct approaches: the van Genuchten formulation and the Kozeny-Carman formula.

At experimental sites exhibiting dual-porosity, the curves diverge significantly in the second phase, corresponding to the emptying of micropores. This discrepancy is due to the van Genuchten model incorporating the soil's dual-porosity characteristic, whereas the Kozeny-Carman formulation does not account for it.

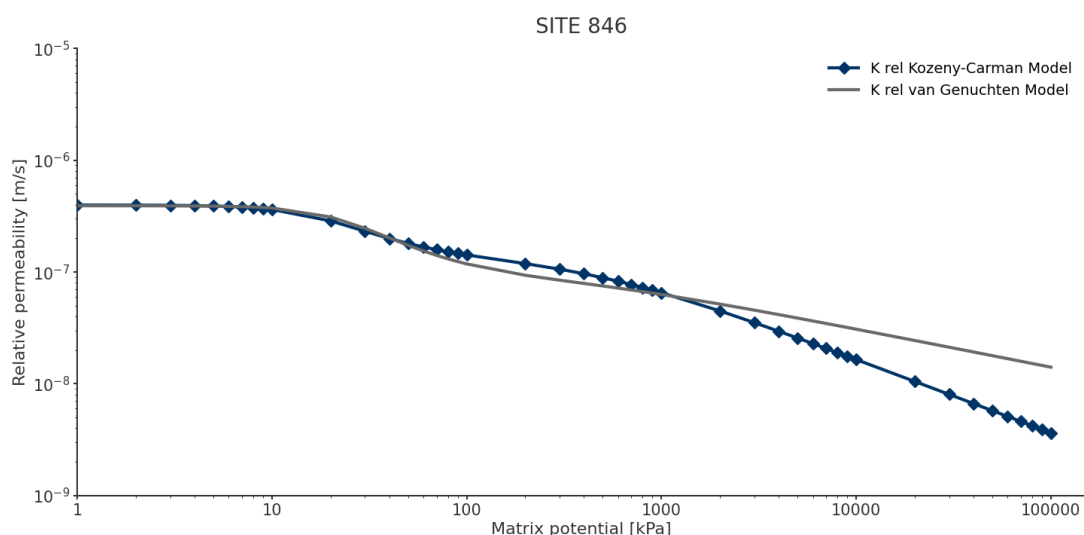
Intrinsic soil hydraulic properties: hydraulic conductivity

The hydraulic conductivity under saturated conditions was quantified through two specific empirical formulations: those of Guarracino (2007) and Mishra and Parker (1990) (Table 5.5). (paragraph 3.3.2),

Table 5.5 - Saturated hydraulic conductivity according to the empirical formulations of Guarracino (2007) and Mishra and Parker (1990).

	k_{sat} (m/s)	k_{sat} (m/s)	k_{sat} (m/s)
	Guarracino (2007)	Mishra and Parker (1990)	Average
SITE 846	5,56E-09	7,77E-07	3,91E-07
SITE 915	1,63E-09	2,06E-07	1,04E-07
SITE 850	4,34E-09	6,88E-07	3,46E-07

Having defined the hydraulic conductivity under saturated conditions (k_s) and knowing the variations in effective saturation (S_e) within a dynamic hydrological system, it is possible to establish the function that describes the change in hydraulic conductivity (k) as a function of the soil's degree of saturation (or matric suction).



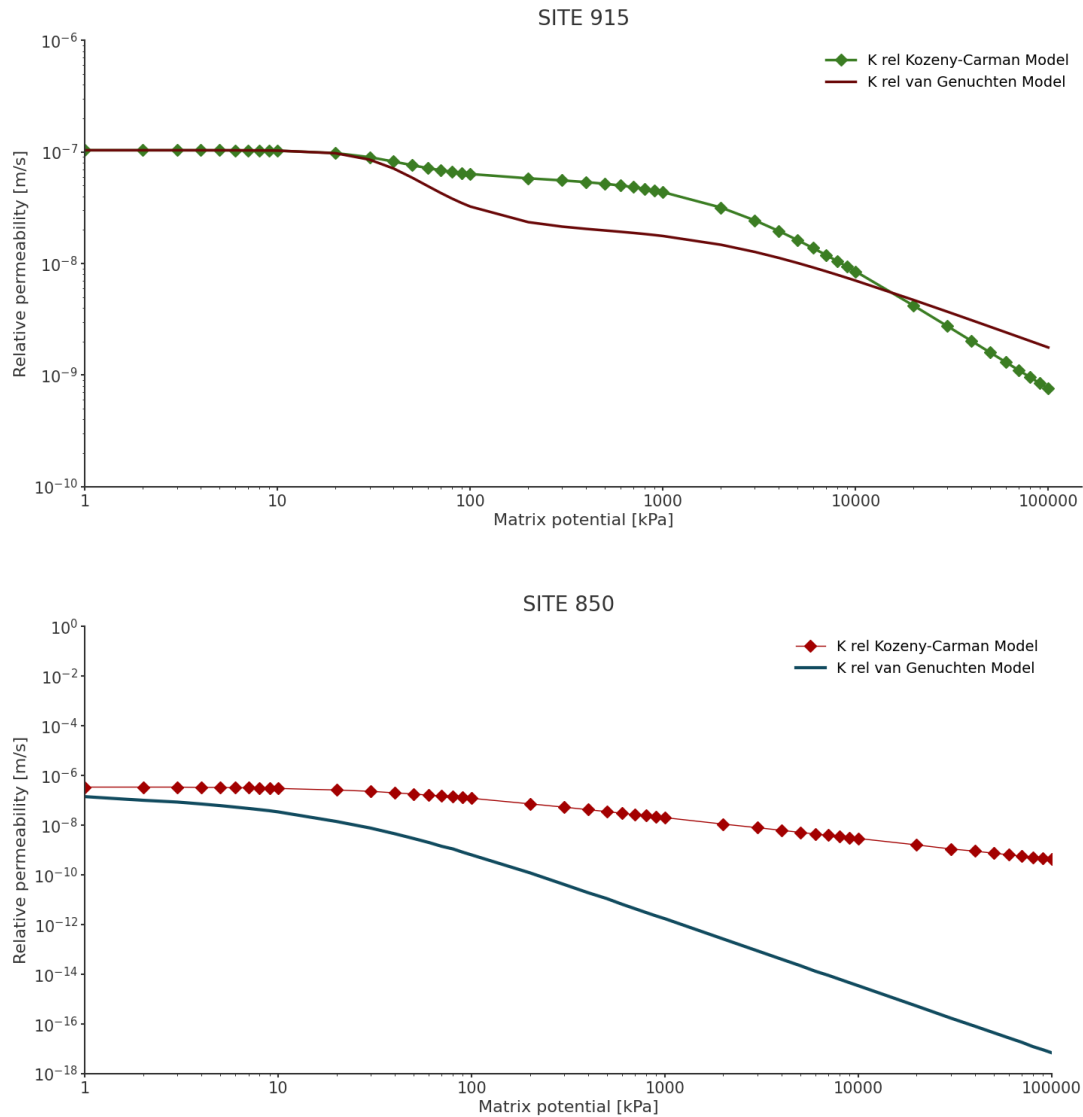


Figure 5.34 - Relative permeability calculated using the van Genuchten and the Kozeny-Carman formulations.

The relationship between the two relative permeability curves for site 850 is consistent with the existing literature. The Kozeny-Carman model is more conservative than the permeability of the van Genuchten model (Paragraph 3.3.2). The Kozeny-Carman model shows a more gradual variation in permeability with a value range that ranges between 10^{-6} m/s and 10^{-10} m/s, reflecting a more conservative flow prediction.

Conversely, the van Genuchten model, which is based on an empirical water retention curve, presents a much sharper variation in hydraulic conductivity. This variation, which ranges from 10^{-6} m/s to 10^{-16} m/s, is due to how the model describes the transition between the saturated and unsaturated states, making it particularly sensitive to changes in matric potential.

Comparison of water retention curves.

Before proceeding with the flow analysis, the soil water retention curves from the three different investigation sites were compared to identify differences in the soil's storage capacity.

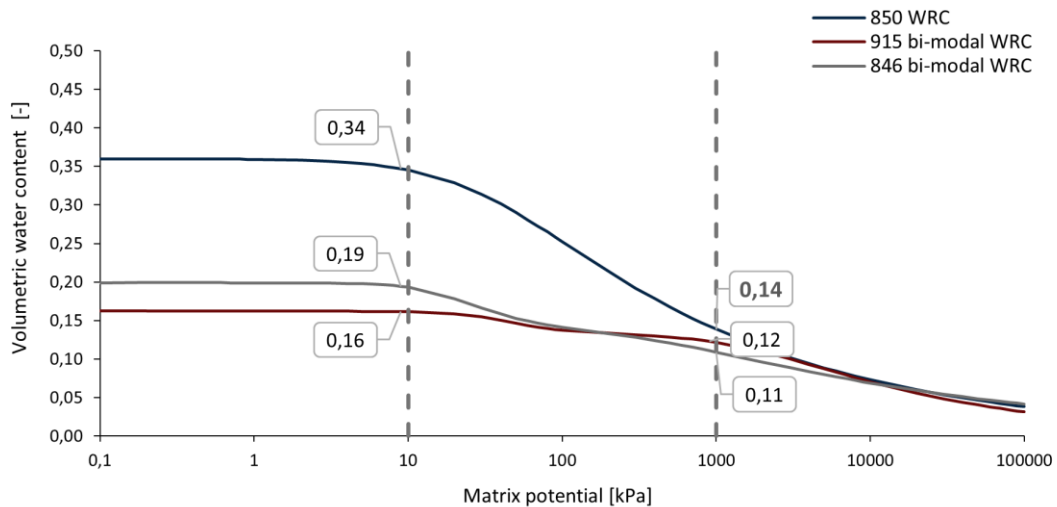


Figure 5.35 - Comparison of the soil water retention curves for the three investigation sites.

The water content values corresponding to suction levels of 10 kPa and 100 kPa are highlighted at the intersection point between the curve and the suction line.

Based on the analysis of the soil water retention curves, it can be observed that the curves for sites 915 and 846 exhibit a similar water storage capacity (Figure 5.35). This is particularly true at suction values of 10 and 100 kPa, where the two curves show nearly identical values, especially at higher suctions. Site 850 presents a situation that is markedly different from the other sites, exhibiting almost double the water retention capacity for the same suction values. This high storage capacity is attributable to a combination of structural factors, including a higher percentage of fine-grained material and an increase in total porosity because less dense due to the backfill wall construction activities (Paragraph 3.1.5).

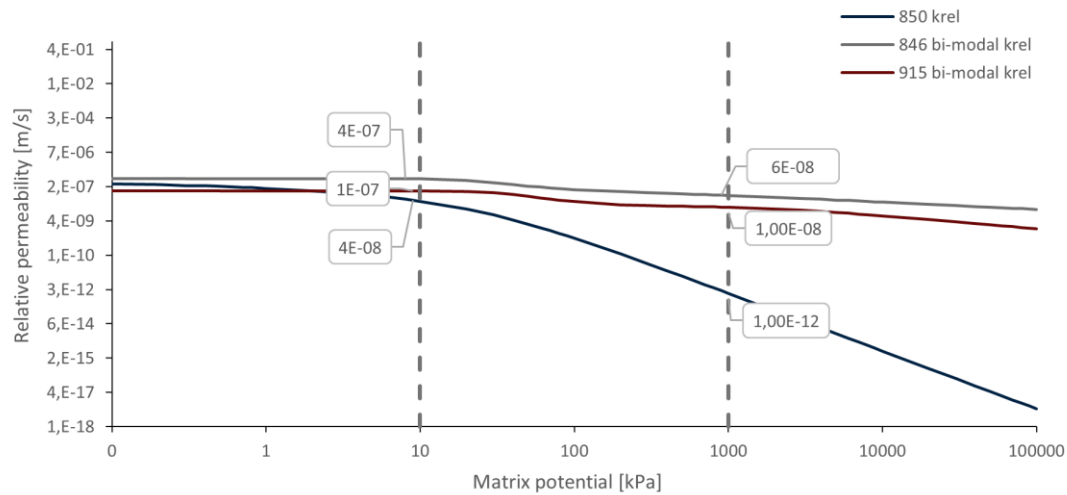


Figure 5.36 - Comparison of the soil relative permeability (k_{rel}) curves for the three investigation sites. The relative permeability values for each investigation site are reported for both intermediate suction (100 kPa) and higher suction (1000 kPa) levels. The permeability values for each site are identified by the intersection point between the respective permeability curve and the corresponding suction line.

Figure 5.36 illustrates the variations in relative permeability across the different experimental sites. This comparison highlighted that, at very low suctions, the three sites exhibit permeability values of remarkably similar orders of magnitude. However, as the suction increases, the permeability at Site 850 decreases substantially compared to the other two sites, with a difference reaching four orders of magnitude. This indicates that soil at Site 850 has a significantly lower hydraulic transfer capacity, particularly under conditions of high suction.

5.2.2 External hydrological forcings

External stresses that act upon the system and cause a variation in its hydrological properties are defined by two main water fluxes: an inflow, consisting of precipitation, and an outflow, represented by evapotranspiration.

For the three sites under examination, the recorded rainfall amount is identical throughout the study period (Figure 5.37). In contrast, the rate of evapotranspiration varies among the different sites, as it is strictly dependent on the characteristics of the ground surface and the type of vegetation cover.

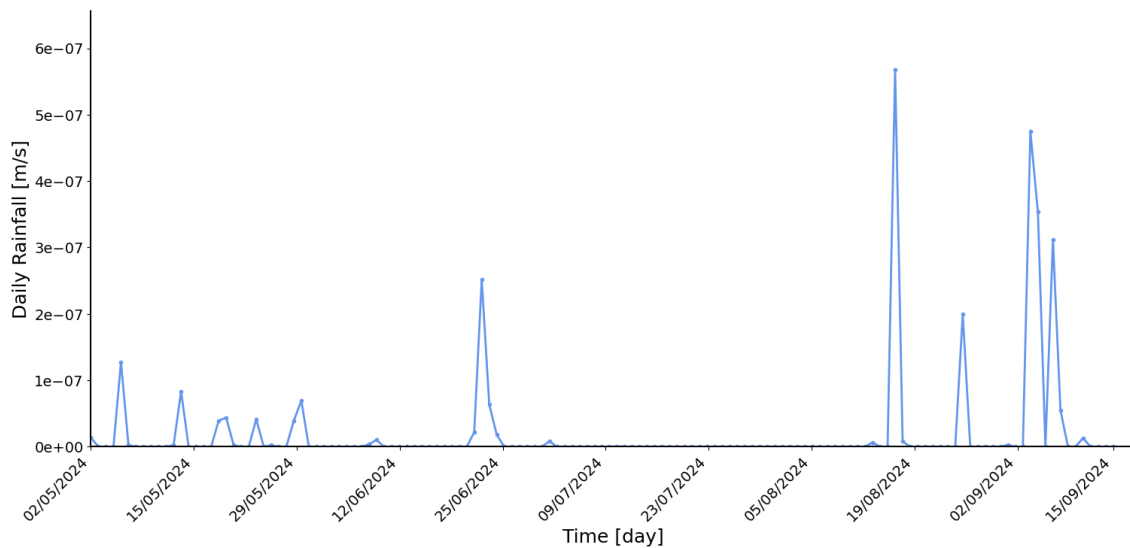


Figure 5.37 – Rainfall trend over the selected period for hydrological modelling.

In the period under consideration, the pluviometric regime is characterised by a wet spell between May and the end of June, including a high-intensity rainfall event. This is followed succeeded by a dry period spanning from July to August, which in turn is followed by some precipitation in August, with the latter events reaching the maximum intensities recorded within the reference period.

For the calculation of potential evapotranspiration (Paragraph 3.3.1.4), base parameters and site-specific parameters were identified.

Base parameters depend on climatic and atmospheric conditions and are common to all three experimental sites. These parameters do not vary according to the specific characteristics of the soil or vegetation. Instead, they describe the general atmospheric conditions for a given geographical area and time period. They include air temperature solar radiation air humidity wind speed (Figure 5.38).

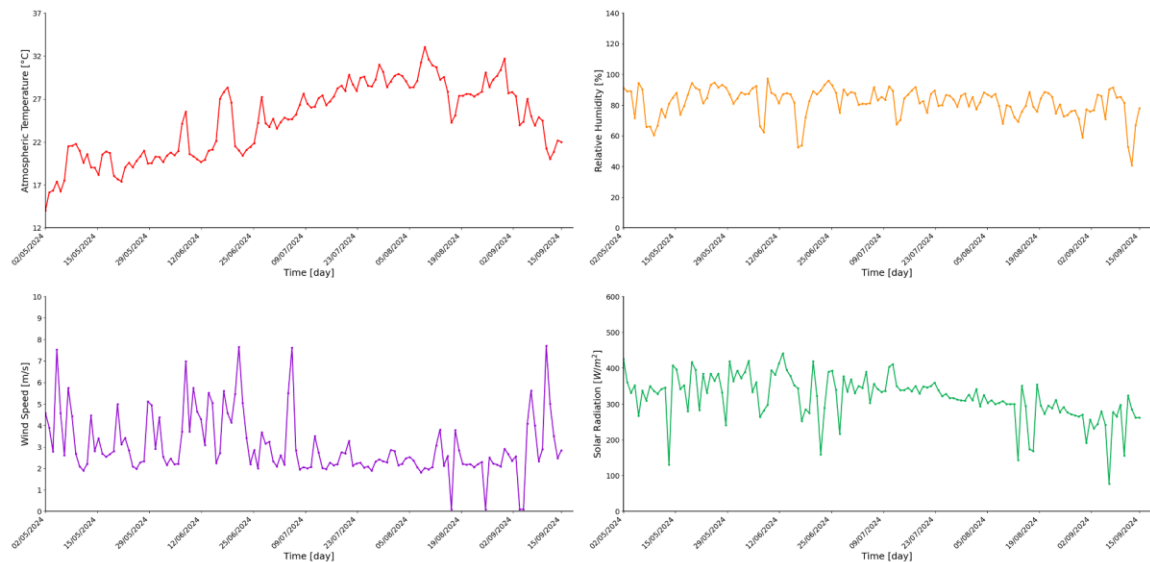


Figure 5.38 – Climatic variables used for the calculation of potential evapotranspiration.

Site-specific parameters play a crucial role in modulating the effective evapotranspiration rate, as they reflect the peculiarities of each local context. These parameters are intrinsically linked to the surface conditions of the soil and the type of vegetation present. For each study site, the site-specific parameters (i.e., surface roughness (z_{0m}), bulk surface resistance (or canopy resistance) (r_c), and albedo (α), have been determined. These values were subsequently integrated with the baseline climatic parameters within the framework of the Penman-Monteith equation (Paragraph 3.3.1.4), thus enabling the calculation of the potential evapotranspiration specific to each investigation site.

Evapotranspiration

Experimental site 846

At site 846, the ground surface exhibits dense spontaneous vegetation, primarily characterised by scrub and shrubs reaching maximum heights of a few metres. Field observations, in conjunction with empirical tables from academic literature (Monteith, 1965, Brutsaert, 1982, and Trombetti and Tagliazucca, 1994), enabled the determination of the surface characteristic parameters required for calculating potential evapotranspiration. To ensure the most suitable and representative parameters for the site, a calibration process was undertaken using GeoStudio (Table 5.6).

Table 5.6 - Parameters for the determination of potential evapotranspiration at site 846.

PET parameters		
z_{0m}	r_c	α
(m)	(s/m)	/
0,2	30	0,26

Figure 5.39 presents the potential evapotranspiration function for the site 846

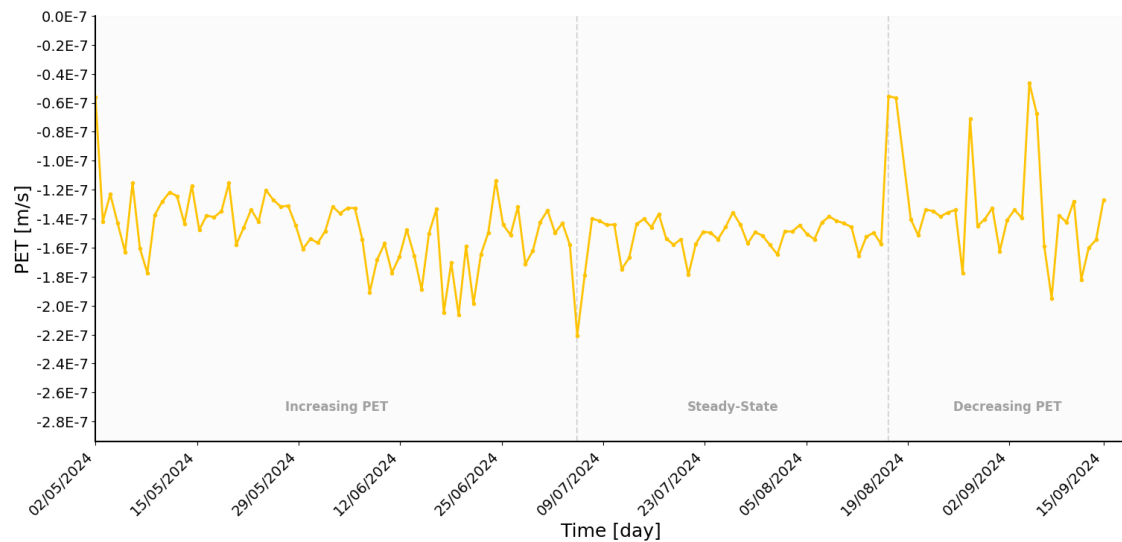


Figure 5.39 – Potential evapotranspiration calculated for the site 846 using the Penman-Monteith model.

The analysis of the derived evapotranspiration function enabled the identification of three distinct regimes, each closely correlated with the specific soil and atmospheric moisture conditions. Initially, during the drying phase, an increasing trend is observed, which is indicative of a high rate of water transfer as the soil becomes progressively drier, reaching peak values of $-2E-7$. Subsequently, the system enters an intermediate phase where the evapotranspiration value stabilises, maintaining a nearly constant trend. Finally, during the wetting period, the evapotranspiration exhibits a clear tendency to decrease, primarily due to the new meteorological input that alters the hydrological and energy balance. Overall, the behaviour of this function consistently mirrors the variation in soil water content, highlighting the strong interdependence between surface hydrological processes and moisture dynamics. The actual evapotranspiration (AET) was determined from the potential evapotranspiration (PET) value, allowing quantifying the amount of water that evaporates from the soil surface and that is transmitted to the atmosphere, taking into account the effective water availability in the soil.

Moreover, the potential evapotranspiration limit was determined, which represents the condition where the soil's water availability becomes lower than the atmospheric water demand for potential evapotranspiration.

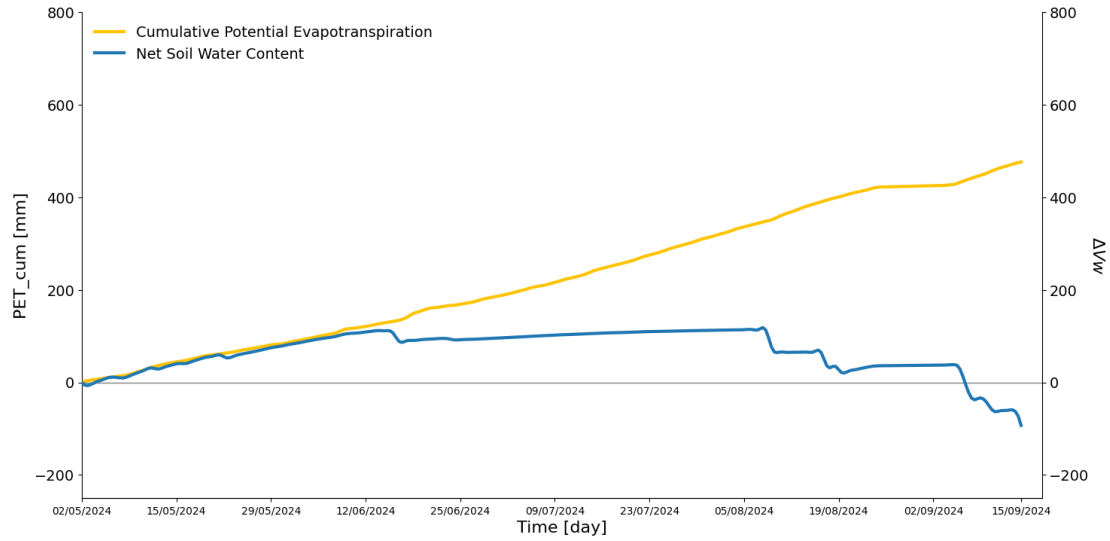


Figure 5.40 – Relationship between cumulative evapotranspiration and soil water content for site 846.

Figure 5.40 depicts the critical functional relationship between cumulative evapotranspiration and soil water content. The observed trend at the experimental site 846 unequivocally highlights the establishment of a limiting pedological water condition for the transfer of moisture to the atmosphere. Specifically, during the period approaching the beginning of the second decade of June, the soil water availability is deficient relative to the atmospheric evaporative demand. Consequently, this inability of the soil-plant-atmosphere continuum to sustain the demand imposed by the surrounding environment demarcates the fundamental transition from the AET regime to the PET regime. The calculated cumulative PET values were found to be consistent with those published in the institutional report by APAT, (2007), thus providing a validation for the magnitude of the simulated hydrological fluxes. Subsequently, the values for calculating the corrective function of Feddes et al. (1978) were determined, namely the parameters Ψ_{leaf} and Ψ_3 . The latter was derived indirectly from the temporal relationship between soil water content and cumulative evapotranspiration.

The point at which these two variables diverge corresponds to a suction value that represents the critical soil suction. The value for the parameter Ψ_{leaf} was derived from literature (Rodriguez et al., 2022) and was subsequently refined via an iterative calibration procedure to ensure its optimal application within the specific context.

Table 5.7 - Parameters for the determination of corrective factor (β).

Ψ_3	Ψ_{leaf}
kPa	kPa
150	1500

Figure 5.41 shows the reduction function for site 846, based on the Ψ_3 and Ψ_{leaf} values that defines the relationship between actual and potential evapotranspiration.

Reduction function_SITE 846

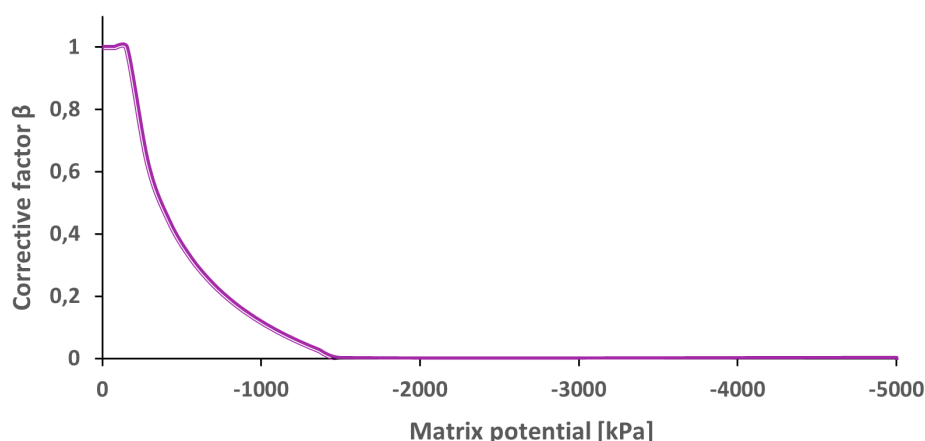


Figure 5.41 – Reduction function that controls the relationship between actual and potential evapotranspiration.

When the suction value is below -150 kPa, AET is equal to PET (condition represented by a straight line in the graph) while when the suction value exceeds -150 kPa, the AET becomes lower than PET, as shown on the graph by a gently decreasing line. Therefore, in this scenario, PET is corrected relative to the actual, considering the trend of the β factor.

Experimental site 915

At site 915, the ground surface is cultivated with a vineyard with rows ≈ 1.8 m height while spontaneous grass between the rows occurs. To realistically calculate the evapotranspiration parameters, site-specific physical data were integrated with empirical tables from the literature (Table 5.8).

Table 5.8 - Parameters for the determination of potential evapotranspiration for the site 915.

PET parameters		
z_{0m}	r_c	α
(m)	(s/m)	/
0,15	50	0,35

Figure 5.42 illustrates the potential evapotranspiration function derived for site 915.

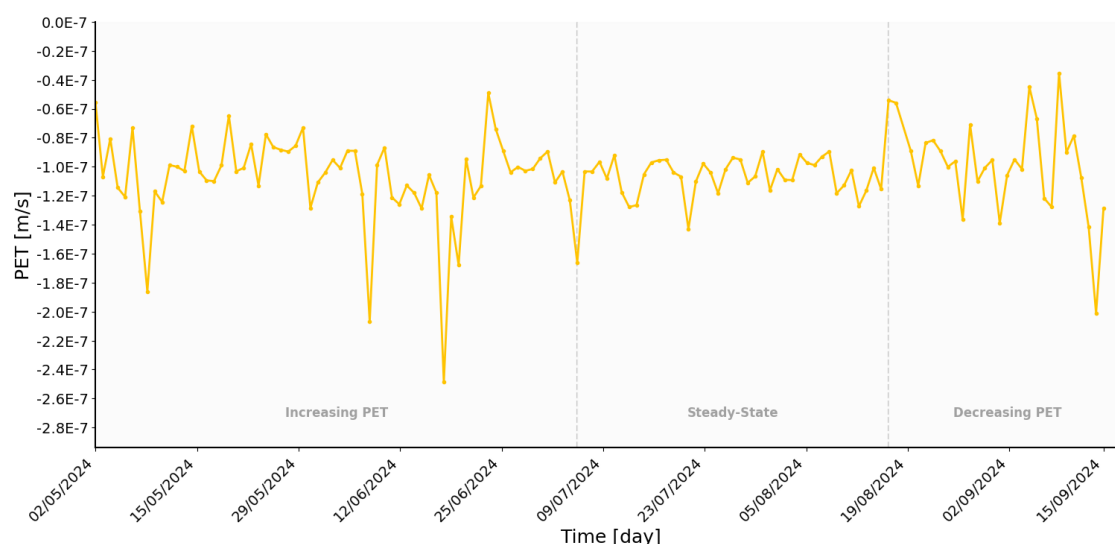


Figure 5.42– Potential evapotranspiration calculated for site 915 using the Penman-Monteith model.

Initially, there is a gradual increase in the rate of evapotranspiration. This is followed by a period where the rate remains nearly constant, before eventually decreasing to lower values. These data are directly consistent with changes in soil water content.

Figure 5.43 shows this relationship between soil water content and cumulative potential evapotranspiration.

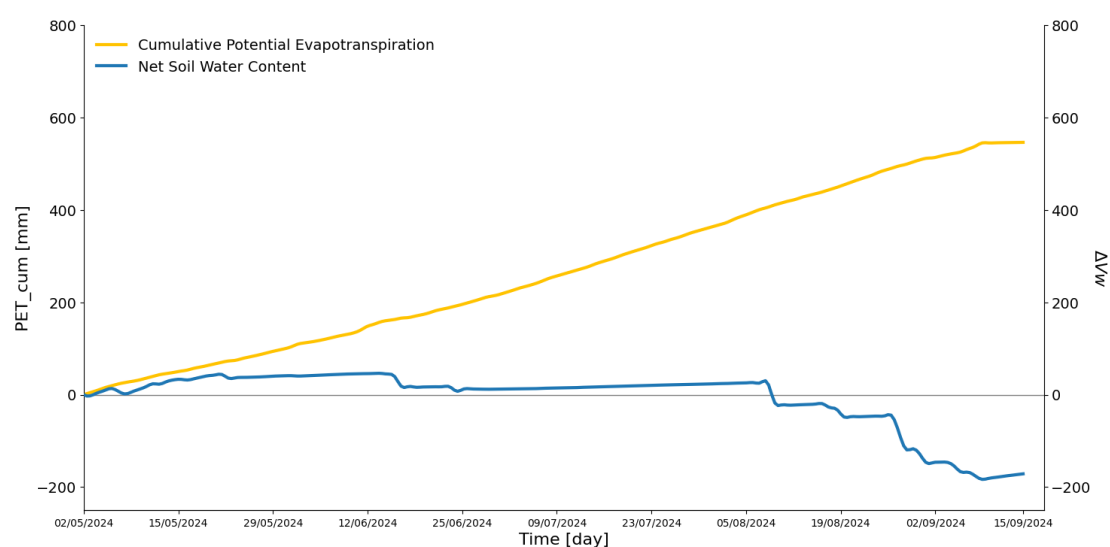


Figure 5.43 – Relationship between cumulative evapotranspiration and soil water content for the site 915.

This relationship demonstrates that the amount of water in the soil is very low, up to influencing the transfer of water from the ground, through the plant, to the atmosphere. This deficit is

particularly evident in the first half of May. Consequently, this temporal point marks the transition from a real to a potential evapotranspiration regime, thus identifying the evapotranspiration limit. The magnitude of PET values determined in the present study was found to be consistent with the historical datasets published by APAT (2007). The values of Ψ_{leaf} and Ψ_3 for calculating the Feddes et al. (1978) corrective function are summarized in Table 5.9.

Table 5.9 - Parameters for the determination of corrective factor (β).

Ψ_3	Ψ_{leaf}
kPa	kPa
50	1500

Reduction function_SITE 915

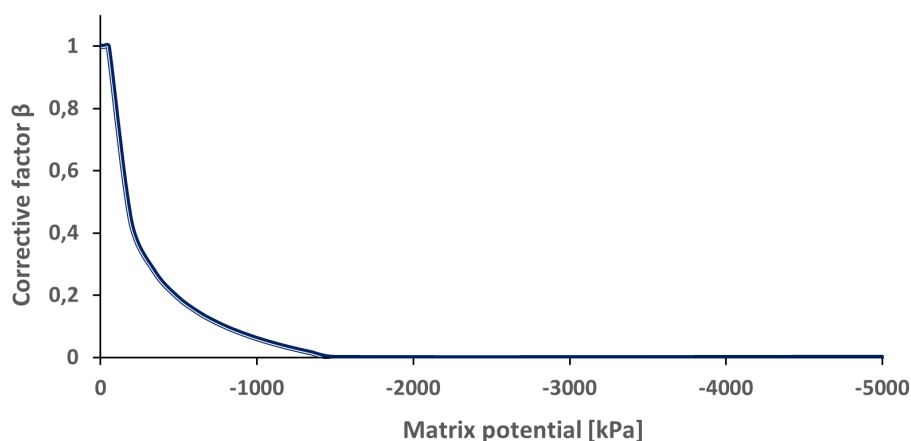


Figure 5.44 – Reduction function that controls the relationship between actual and potential evapotranspiration.

Figure 5.44 illustrates the reduction function for site 915. In this instance, for suction values below -50 kPa, AET is equal to PET, which is represented by a continuous trend with a value of 1 on the graph. When the suction value exceeds -50 kPa, the soil can no longer transfer the required amount of water to the atmosphere. Consequently, the ratio between AET and PET falls to a value below 1. It is important to note that this reduction is not sudden but occurs gradually, as shown by the curve trend.

Experimental site 850

In the case of site 850, the soil surface presents a largely uniform cover of grass and spontaneous bushes, with a variable height of 40-60 cm. The parameters that most accurately describe the evapotranspiration rate for the specific site conditions are summarized in Table 5.10.

Table 5.10 - Parameters for the determination of potential evapotranspiration for the site.

PET parameters		
z_{0m}	rc	α
(m)	(s/m)	/
0,07	30	0,23

Figure 5.45 represents the potential evapotranspiration function, whose trend shows a clear increase in the potential evapotranspiration rate in the first part of the analysed period, reaching a peak at the end of June. Subsequently, a period of stability is observed, where the evapotranspiration rate remains almost constant, followed by a gradual decrease. This temporal trend of potential evapotranspiration is consistent with the variations in soil water content recorded within the soil.

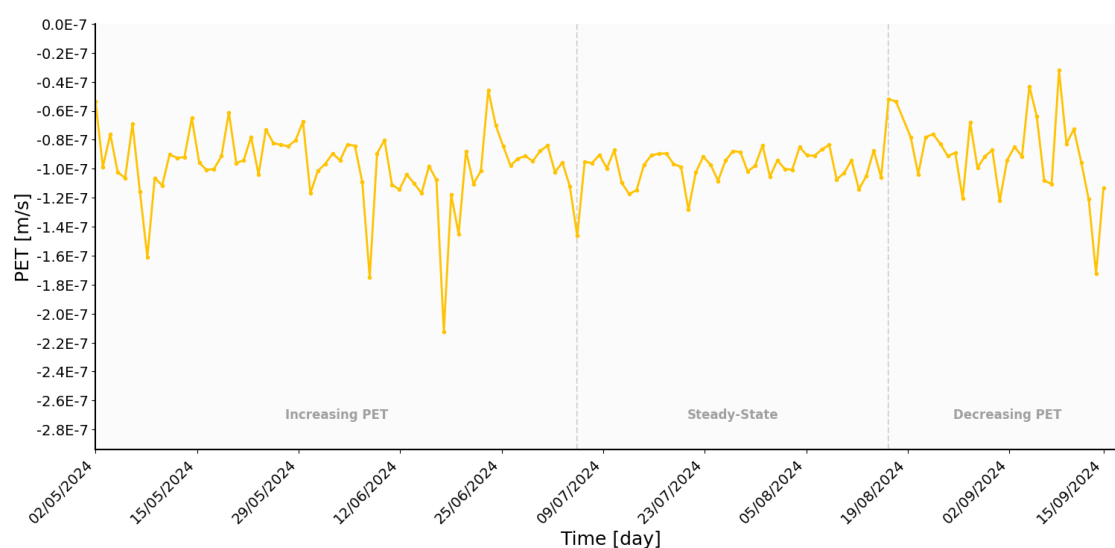


Figure 5.45 – Potential evapotranspiration calculated for site 850 using the Penman-Monteith model.

The cumulative potential evapotranspiration was compared, in a temporal relationship, with the available soil water (Figure 5.46).

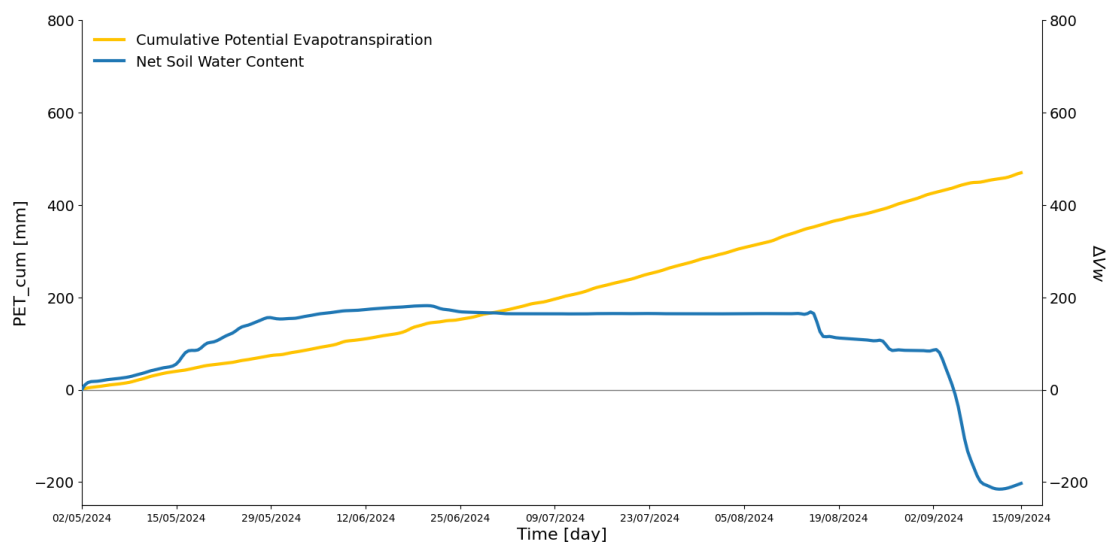


Figure 5.46 – Relationship between cumulative evapotranspiration and soil water content for the site 850.

The analysis of the relationship between cumulative PET and soil water content demonstrates that during the period spanning from May to early June, the soil's water availability is significantly greater than the atmospheric evaporative demand. Consequently, the soil-plant system is fully capable of meeting the atmospheric water requirement. Subsequently, from that point onwards, a stabilisation of the soil water content at a constant value is observed. This implies that the soil is no longer able to meet the atmospheric water demand, thereby reaching the evapotranspiration limit. The obtained cumulative PET data were validated through a direct comparison with the observations and records published by APAT (2007) confirming that the simulated hydrological fluxes are representative of the reference climatic conditions.

Table 5.11 - Parameters for the determination of corrective factor (β).

Ψ_3	Ψ_{leaf}
kPa	kPa
1300	1500

Considering the parameters Ψ_3 and Ψ_{leaf} (Table 5.11), the function describing the variation between PET and AET was found (Figure 5.47).

Reduction function_SITE 850

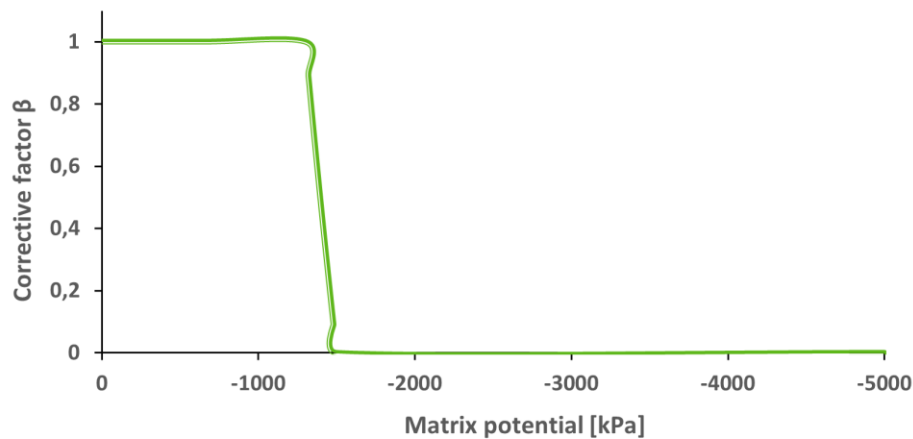


Figure 5.47 – Reduction function that controls the relationship between actual and potential evapotranspiration.

For suction values below -1300 kPa, AET is equal to PET, and consequently, the corrective factor is equal to 1. Once this critical threshold is exceeded, PET decreases more rapidly and sharply than in previous cases, following the behaviour of the corrective function.

5.3 HYDROLOGIACL MODELL CALIBRATION

The intrinsic hydrological properties of the soil and site-specific boundary conditions were integrated into a numerical model using GeoStudio software. This integration is aimed at performing a Finite Element Method (FEM) analysis, in accordance with the procedure outlined in Section 3.3.2. The primary objective of this modelling is twofold: the validation of the hydrological model and the determination of the pore-water pressure distribution within the soil profile for all investigated sites.

5.3.1 Numerical model setup

The cross-section of the embankment for each experimental site was reconstructed within the software GeoStudio, based on the field data described in Paragraph 2.5, such as terrace length, inclination, and thickness of the embankment located immediately behind the retaining wall (Figure 5.48).

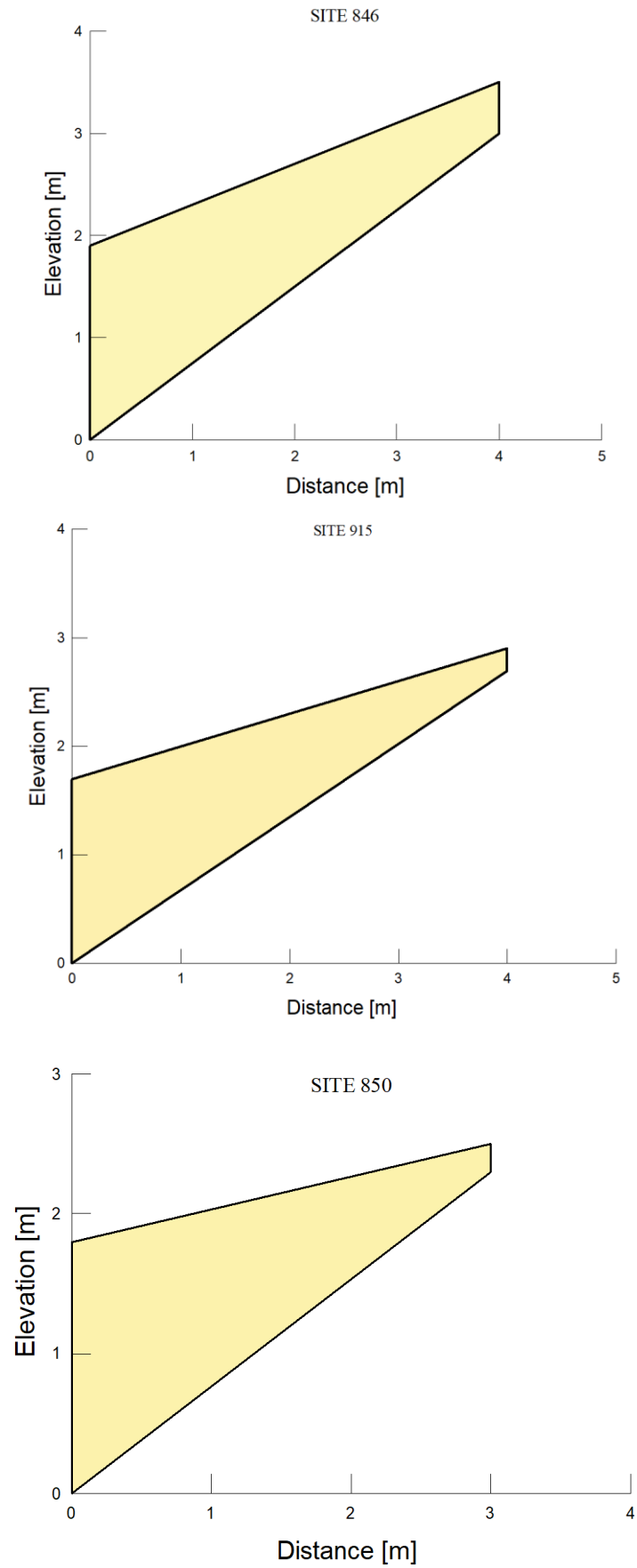


Figure 5.48 – Construction of the geometry of the three experimental sites in GeoStudio.

Input hydrological characteristics, including the soil water retention curve and the relative permeability function determined experimentally, were implemented into the model.

A sensitivity analysis on relative permeability was conducted for each site. Specifically, numerical simulations were performed using both relative permeability calculated with the van Genuchten method the Kozeny-Carman model and the outcomes were then compared. This approach was aimed at assessing which of the two methodologies was more suitable to simulate the hydraulic conditions governing water transfer within the soil profile. Hydrological boundary conditions were implemented to regulate the water exchange between the model and the surrounding environment. A no-flow condition (zero flux) was applied to the lower boundary. This was necessary to simulate the presence of an impermeable substrate (bedrock), which is assumed not to influence the hydrological variations of the slope. The lower lateral boundary of the model (identified in Figure 5.50 by a blue line and triangles) was set up with a permissible flow condition to simulate the phenomenon of seepage. It should be noted that the retaining wall structure was not explicitly modelled, as the primary objective of the analysis was the assessment of the hydrological conditions within the terrace embankment.

An inflow condition, representative of the rainfall intensity recorded between May 2, 2024, and September 15, 2024, was imposed at the upper boundary.

Finally, the outflow boundary condition, correlated with the E rate, was applied to the superficial soil layer, whose thickness was defined based on the maximum root depth observed at each investigated site (Paragraph 3.3.5) (Figure 5.49). The potential ET rate was then spatially distributed within the root-delimited soil volume, thereby simulating the spatial dynamics of water uptake by the vegetation. During the setup of the PET function, the GeoStudio software allowed for the application of a corrective function, termed the "modifier", which was previously calculated for each site (Paragraph 5.2.2) in order to control the relationship between effective and potential evapotranspiration.

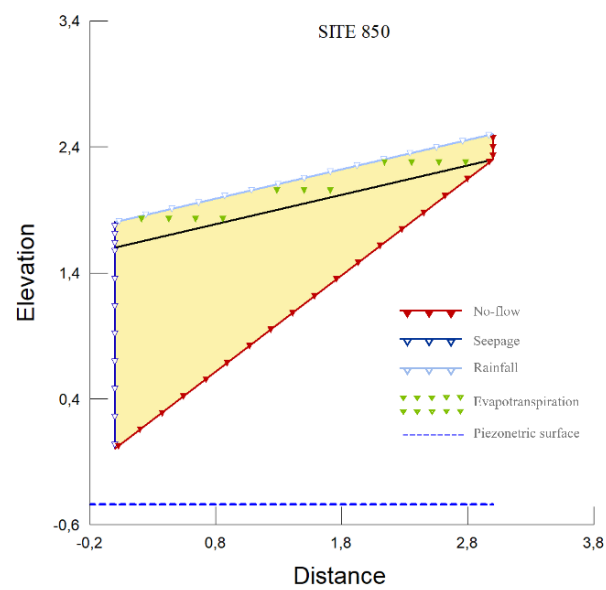
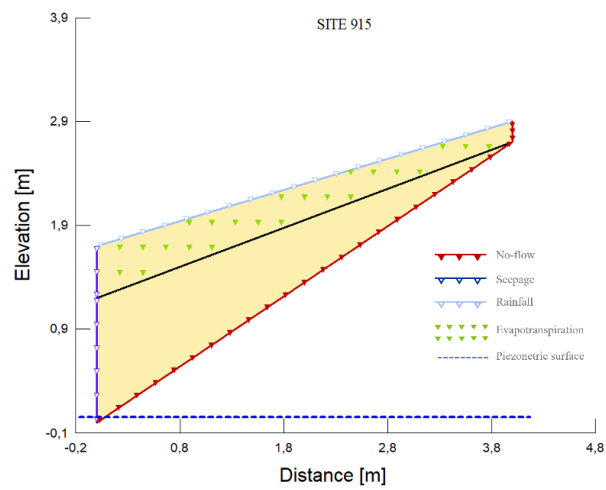
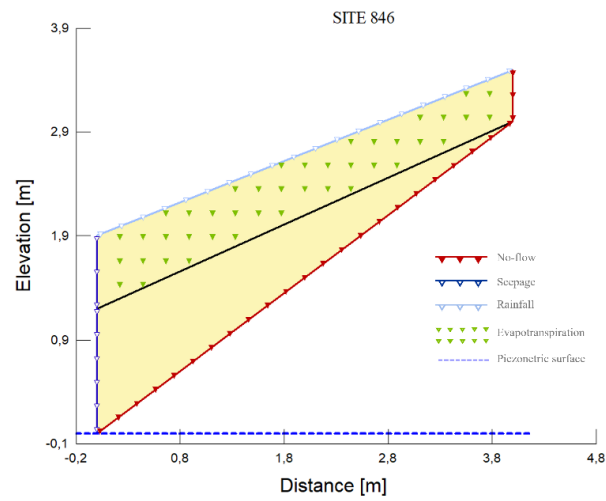


Figure 5.49 –Boundary and initial conditions set up in GeoStudio for each experimental site.

The initial condition for each experimental site was established by imposing a soil suction value of 20 kPa for all three experimental sites. At this specific suction value, the water content differs for each site as a function of its WRC. To ensure an accurate and consistent representation of the initial suction and water content values, a fictitious water table was introduced. Specifically, the water table was positioned at a depth calculated to generate a suction of 20 kPa at the observation point corresponding to the simulated sensor location at a 50 cm depth. This methodology facilitated the generation of initial pore-water pressure distributions consistent with the data measured by suction sensors. To aid the analysis of the simulation results, specific observation points were inserted for each site at the depth of the intermediate sensor installation. Based on the numerical model developed within the GeoStudio software environment, a transient flow analysis was conducted for each experimental site employing the SEEP/W module.

5.3.2 Numerical model validation

The transient flow analysis compared the observed data with the hydrological modelling employing the Kozeny-Carman and van Genuchten relative permeability models (Figure 5.50). Both models were shown to successfully simulate the temporal evolution of VWC, capturing both the gradual decrease attributed to soil drying and the rapid increases induced by re-wetting events, allowing to validate the applicability of both approaches (Kozeny-Carman and van Genuchten) for simulating transient flow.

However, the van Genuchten model showed greater accuracy in simulating the flow curve. This may be attributed to the direct calculation of relative permeability from the soil water retention curve parameters. The Kozeny-Carman model, conversely, relies primarily on the relationship between the degree of saturation and saturated permeability.

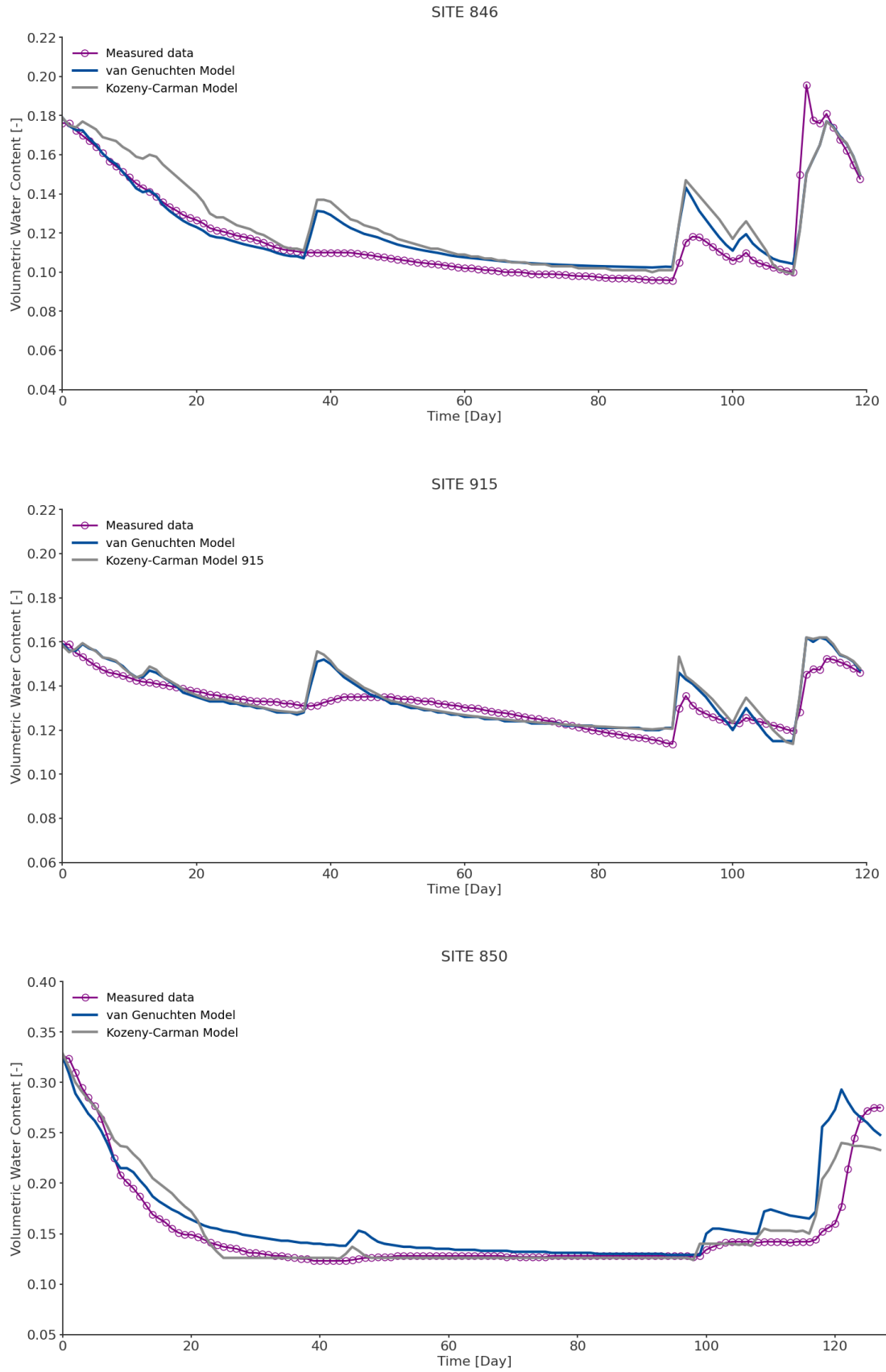


Figure 5.50 – Hydrological modelling results in SEEP/W for the three experimental sites.

Finally, it was observed that the simulated peaks in VWC (Figure 5.50) were more pronounced than the observed data. To interpret this discrepancy, the simulation results were compared with the pluviometric data used as input for the model (Figure 5.51).

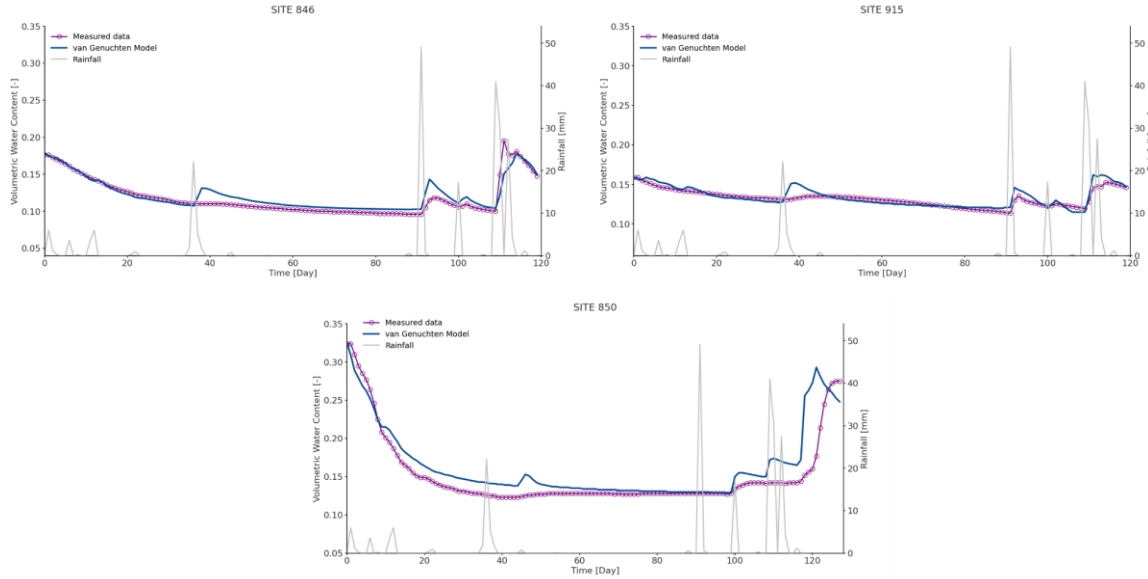


Figure 5.51 – Comparison between the simulation results and pluviometric data.

The simulated VWC correlated well with the rainfall peaks, also showing a slight delay, attributed to the infiltration process. However, the simulation overestimated VWC, likely due to an underestimation of surface runoff and, consequently, an incomplete representation of hydrological processes within the model.

5.3.3 Pore water pressure numerical simulation

Figures 5.52 and 5.54 show the pore water pressure distribution at each experimental site, specifically comparing two extreme hydrological scenarios. Figure 5.52 is indicative of the drying phase and shows the pore water pressure distributions recorded at the critical point, namely the minimum water content. Conversely, Figure 5.54 describe the wetting phase, depicting the pore pressure distributions during the condition of maximum VWC.

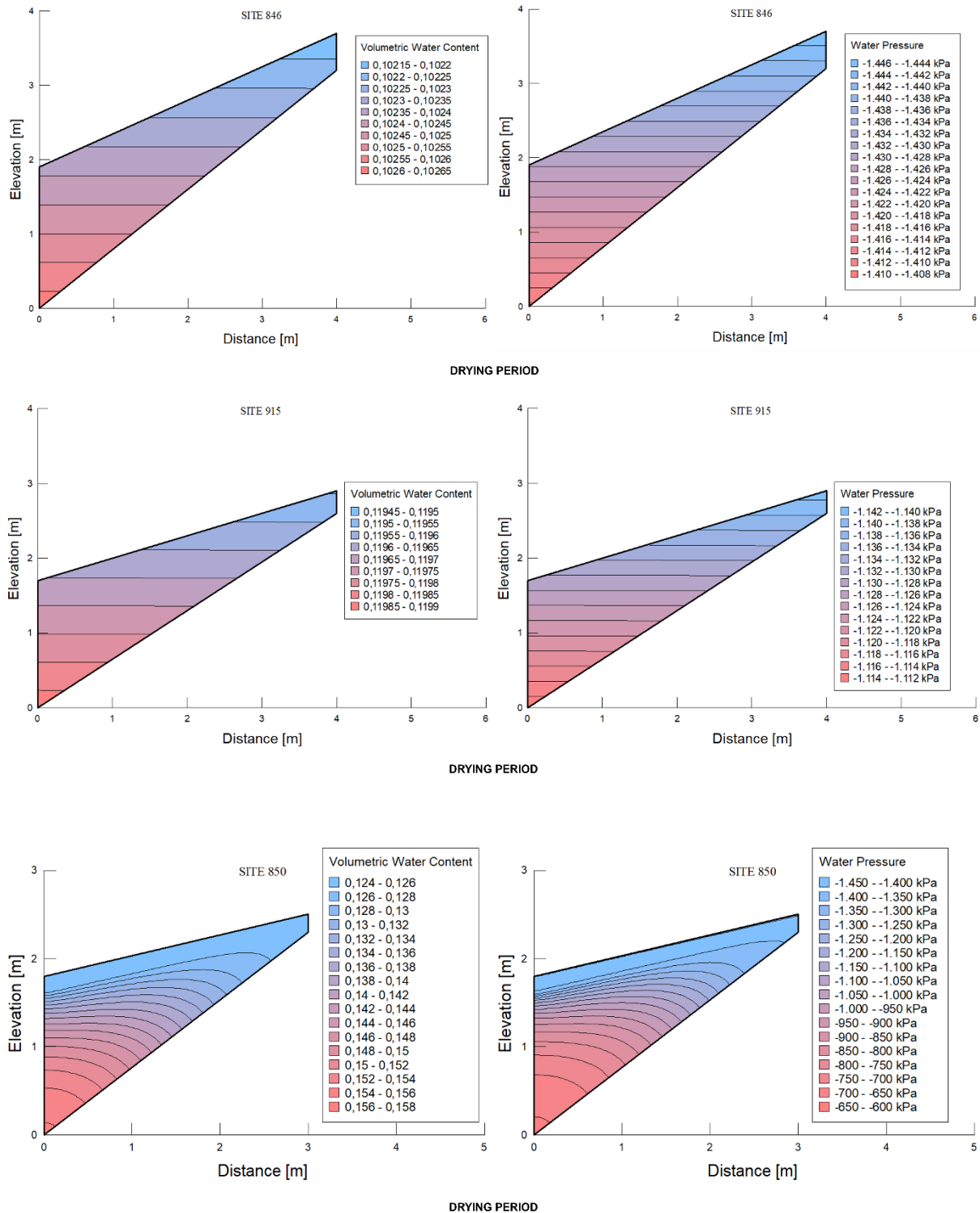


Figure 5.52 – Pore pressure distribution in relation to the variation in extreme VWC values representative of the drying phases.

The analysis conducted on the drying phase revealed a vertical variation in soil suction consistent with depth at all experimental sites. The highest values of negative pore pressure were observed near the soil surface. This condition is primarily attributable to two factors: direct

interaction with the atmosphere, which induces water evaporation, and water uptake by the root systems of the existing vegetation. Both processes generate capillary tension, leading to an increase in suction. Conversely, soil suction values progressively decreased with increasing depth. This trend is associated with the reduction in the influence of surface factors and the greater stability of subsoil water conditions. Consequently, the variation in the pore water pressure gradient reflects the dynamics of soil profile dehydration due to environmental changes. The negative pore pressure values differ both in magnitude and range among the experimental sites, likely based on the specific hydrological and environmental conditions of each site (Table 5.12).

Table 5.12 - Range of values of pore water pressure and VWC variation during the drying period.

	DRYING PERIOD			
	VWC range		PP range	
	/		kPa	
	min	max	max	min
St_846	0,1021	0,1026	-1446	-1408
St_915	0,1194	0,1199	-1142	-1112
St_850	0,124	0,158	-1450	-600

Site 846 exhibited the greatest dehydration, with the lowest water content values uniformly distributed throughout the entire profile. This homogeneity is reflected by an equally uniform pore pressure characterised by high negative values (suction). Site 915 showed a trend similar to Site 846 regarding the uniformity of water distribution, suggesting a homogeneous drying process. However, the moisture content values are higher, indicating a lower water loss compared to Site 846. Site 850 presents a markedly different behaviour, with a non-uniform distribution of water content. A clear vertical stratification is observed: moisture is minimal at the surface and progressively increases with depth, indicating a greater capacity for water storage in the deeper layers. This non-uniform water content generates a wide range of negative suction (pore pressure). Suction is maximum at the surface, drastically decreasing with increasing depth, showing a significant difference between shallow and deep values.

These differences in the response to drying can be explained by the interaction between surface extraction mechanisms and the intrinsic soil hydraulic properties. The release of water from the soil during drying phases is a process primarily driven by evapotranspiration. This factor, which is in turn modulated by the type of vegetation, determines the variations in the soil water

balance. It is important to note that evapotranspiration does not modify the shape of the WRC, which is primarily controlled by the intrinsic soil properties.

Consequently, a higher evapotranspiration rate will generate greater suction, but the VWC variation in response to suction depends on the specific shape of the WRC. This influence is fundamental because it determines the amount of water present in the soil and, thus the distribution of pore pressures that in turn affect its stability. Therefore, the evapotranspiration rate is strongly correlated with the type and architecture of the vegetation, which modulates the quantity and depth of water extraction. At Sites 846 and 915, the root systems show a homogeneous distribution along the profile, which influences approximately 44% of the total soil thickness (e.g., 0.7 m out of 1.7 m at Site 846; 0.5 m out of 1.16 m at Site 915), promoting a consistent water extraction, thus resulting in a uniform distribution of moisture and suction. At Site 850 the root system is concentrated predominantly in the superficial layer (0.2 m), affecting only about 15% of the average thickness (1.3 m) (Figure 5.53), confining ET processes to the shallow layers. Therefore, the deeper layers maintain greater water availability and, consequently, a significantly lower negative pore pressure. The variations in water extraction highlight that the root geometry significantly alters the hydrological conditions. The percentage of soil thickness influenced by the roots (Figure 5.53) is a key parameter that identifies the portion of the soil subjected to effect of suction, with resulting implications for moisture content and stability.

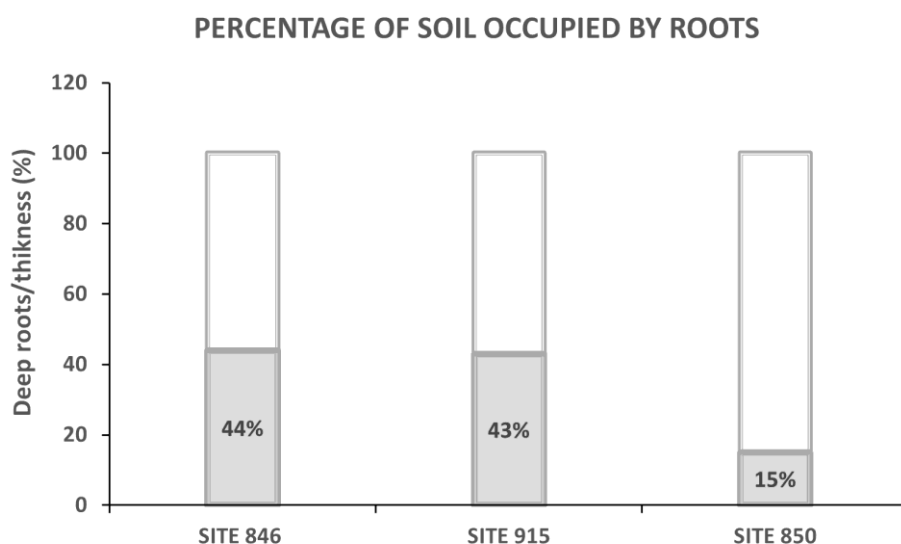


Figure 5.53 – Average percentage of soil thickness affected by root.

Figure 5.54 shows the graphs illustrating the change in pore water pressures during the wetting phase for each experimental site.

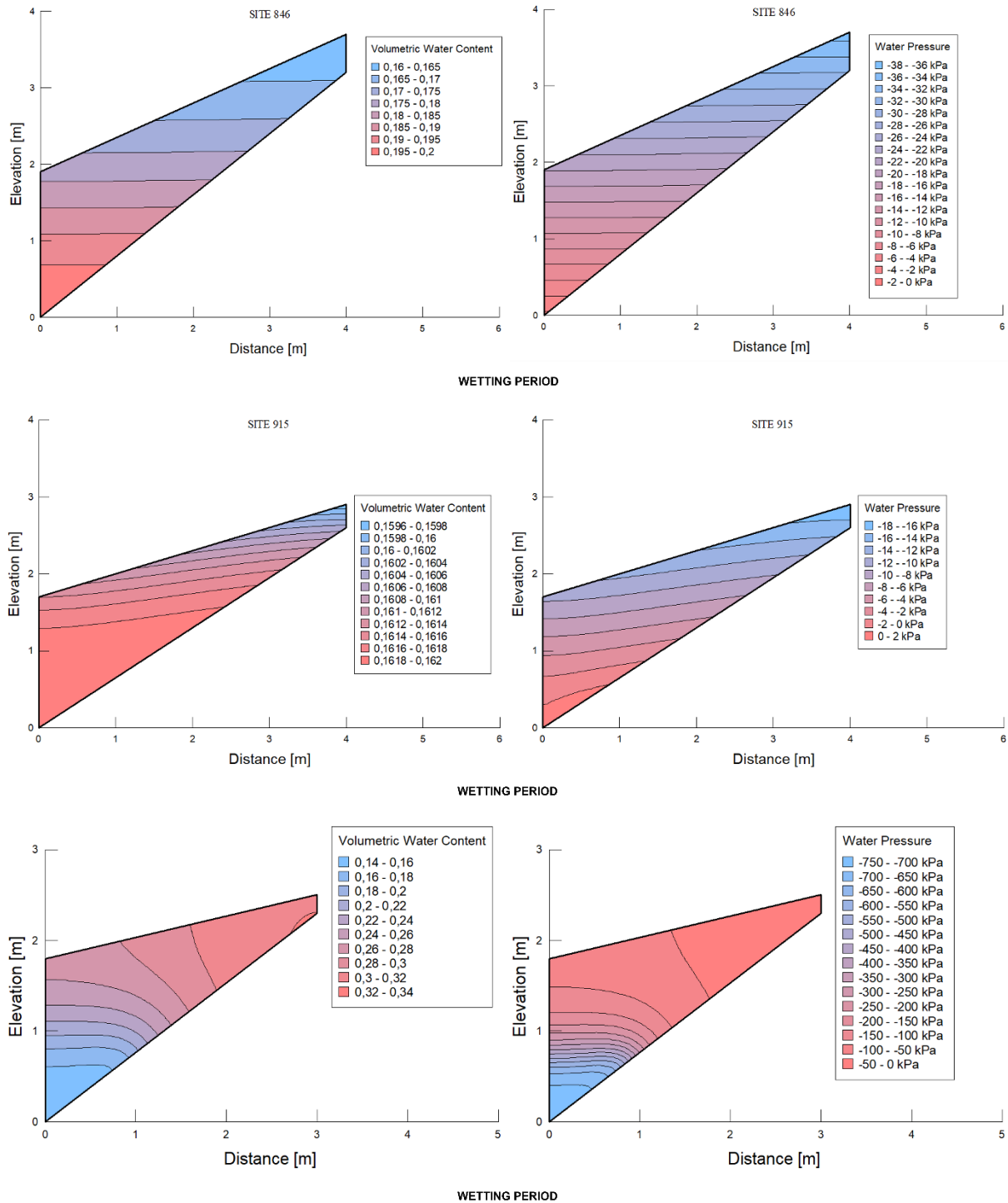


Figure 5.54 – Pore pressure distribution relative to the variation in extreme VWC values representative of the wetting phases.

The analysis of pore-water pressure profiles revealed that the soil water saturation level, even during the VWC peak, never reached the threshold of full saturation. This evidence is of

fundamental importance, as it confirms the absence of significant free water accumulation and, consequently, the non-generation of substantial positive hydraulic pore-water pressures within the soil matrix. This hydrological regime is primarily attributable to the soil inherent granulometric properties, which impart a high hydraulic conductivity, thereby preventing the complete saturation of the soil pores. The persistent occurrence of negative pore-water pressure values represents clear evidence of the continuous action of capillary suction. This force maintains the water within the soil's pore spaces in a state of tension, thereby confirming the prevailing unsaturated regime.

Table 5.13 - Range of values of pore pressure and VWC variation during the wetting period.

	WETTING PERIOD			
	VWC range		PP range	
	/		kPa	
	min	max	max	min
St_846	0,16	0,2	-38	0
St_915	0,159	0,162	-18	2
St_850	0,14	0,34	-750	0

The analysis of Table 5.13 highlights a significant variability in suction and water content parameters among the experimental sites during the wetting phase.

Site 850 exhibited the maximum VWC, but also the greatest vertical heterogeneity, with minimum values of 0.14 in the deeper layers. This heterogeneity did not favour a uniform moisture distribution and resulted in the highest suction values, approximately 90 times greater than the other sites at the same depth. In contrast to sites 846 and 915, site 850 showed a peculiar inversion of the hydraulic gradient, with the suction peak localised in the deeper layers of the slope.

Sites 846 and 915 showed a more uniform water content distribution with depth, with site 846 characterised by an overall higher VWC, concentrated in the lower part and gradually decreasing towards the surface (where it was similar to site 915). This greater variability in VWC at site 846 translates into higher suction values and a wider range. Conversely, at site 915, with a nearly uniform VWC distribution, recorded the lowest variability in suction values. During the wetting phase, the soil hydrological balance is primarily governed by precipitation and subsequent infiltration. Consequently, differences in soil suction are mainly attributable to intrinsic hydrological characteristics (e.g., relative permeability) and geometrical properties (e.g., thickness and slope).

For instance, the lower negative pore pressure (lower suction) recorded at Site 915 may be correlated with specific slope geometrical characteristics. The combination of a smaller cover thickness and a less slope inclination can increase the water storage capacity. At Site 850, a distinctive hydrological dynamic can be assumed: low suction (high water content) in the shallow layers and extremely high suction values in the deeper strata.

The peculiar hydrological behaviour observed at Site 850, which manifests itself as low suction at the surface and extremely high suction at depth, can be explained by some specific soil physical features. Indeed, the reconstruction of the wall and of the embankment involved extensive soil reworking. This resulted in poor soil compaction, increasing its total porosity. Moreover, the soil used to construct the embankment was sieved to remove large cobbles and pebbles, likely altering the percentage of fine materials. This may have produced a capillary distribution enriched with small and medium-sized pores. The prevalence of small pores gives the surface horizon a high-water retention capacity. This structure could generate a high-water retention capacity at the surface horizon, resulting in the low suction observed. Conversely, the capillary distribution drastically reduces the size and connectivity of the channels through which water moves. This limitation on water mobility would be the determining factor preventing rapid downward water transfer, thus explaining the presence of extremely high suction in the deeper layers.

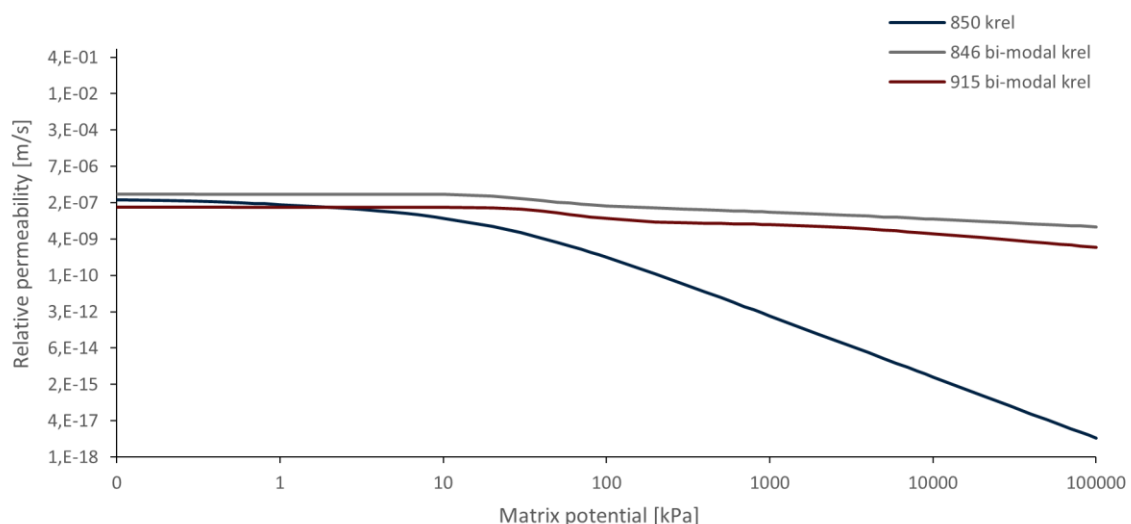


Figure 5.55 - Relative permeability comparison (van Genuchten model) for the three experimental sites.

The high suction observed in the deeper part of the soil profile may be attributable to the soil conditions resulting from the previous drying phase. Due to the low soil permeability, these conditions may not have been removed yet by subsequent rainfall events. Therefore, the

relatively low hydraulic conductivity can be the primary cause of the marked inhomogeneity of the water content observed along the vertical soil profile. Water accumulates in the shallow layers before being slowly drained, creating a significant water gradient. This situation contrasts with that of the other sites, which exhibited a significantly higher hydraulic conductivity (Figure 5.55). In these sites, the downward drainage of water seems much more efficient and rapid, resulting in a more homogeneous water content distribution.

5.4 SLOPE STABILITY ANALYSIS: THE EFFECT OF PORE WATER PRESSURE

Soil wetting and drying cycles exert a significant influence on the hydrological response of slopes, altering the volumetric water content and the pore-water pressures. This variation directly impacts the hydro-mechanical behaviour of the soil, which is a determining factor for slope stability.

Previous seepage analyses allowed for the definition of the pore-water pressure distribution during different hydrological phases.

Based on these results, a limit equilibrium stability analysis was undertaken to quantify the influence of the pore-water pressures under the varying hydrological conditions of terraces at each experimental site. This was conducted by integrating the SLOPE/W module of GeoStudio with the results obtained from the seepage analysis (Paragraph 5.3.3).

Considering that the SLOPE/W module only permits stability analysis for discrete time steps, a specific methodological approach was implemented to track the temporal evolution of the factor of safety. The analysis was performed iteratively, considering discrete time intervals (typically with a daily step) for the entire study period (from 02/05/2024 to 15/09/2024). For each interval, a distinct limit equilibrium stability analysis was executed, allowing for the reconstruction of the factor of safety trend as a function of the pore-water pressure variations over time.

5.4.1 Numerical model setup

The limit equilibrium analysis was performed using the geometry derived from the preceding flow analysis, and by integrating mechanical properties representative of the investigated sites into the numerical model (Table 5.14). The Mohr-Coulomb constitutive model was selected to describe the mechanical behaviour of the cover material.

Table 5.14 – Input mechanical parameters for each experimental site.

	SITE 846	SITE 915	SITE 850
γ (kN/m ³)	19	19,5	17,8
c' (kPa)	0	0	0
ϕ' (°)	32	32	32

The analysis included the evaluation of the variation in the soil's unit weight, which is critical in the context of unsaturated soils, by incorporating into the numerical model the site-specific WRC.

Furthermore, soil suction was implemented as an additional cohesive force, thereby increasing the soil's shear strength. Consequently, this shear strength was appropriately specified in the software as a function of the water content, strictly following the trend defined by the soil's WRC. Finally, the probable entry and exit points of the slip surface was defined using the "Slip Surface Entry and Exit" command. This command allowed to define the portion of the ground surface where a potential slip surface is most likely to be originated, thereby identifying the searching area for the factor of safety calculation.

5.4.2 Numerical model results

The results, expressed in terms of the critical factor of safety (SF), allowed for the definition of a dynamic framework of slope stability in relation to different soil hydrological conditions (Figure 5.56).

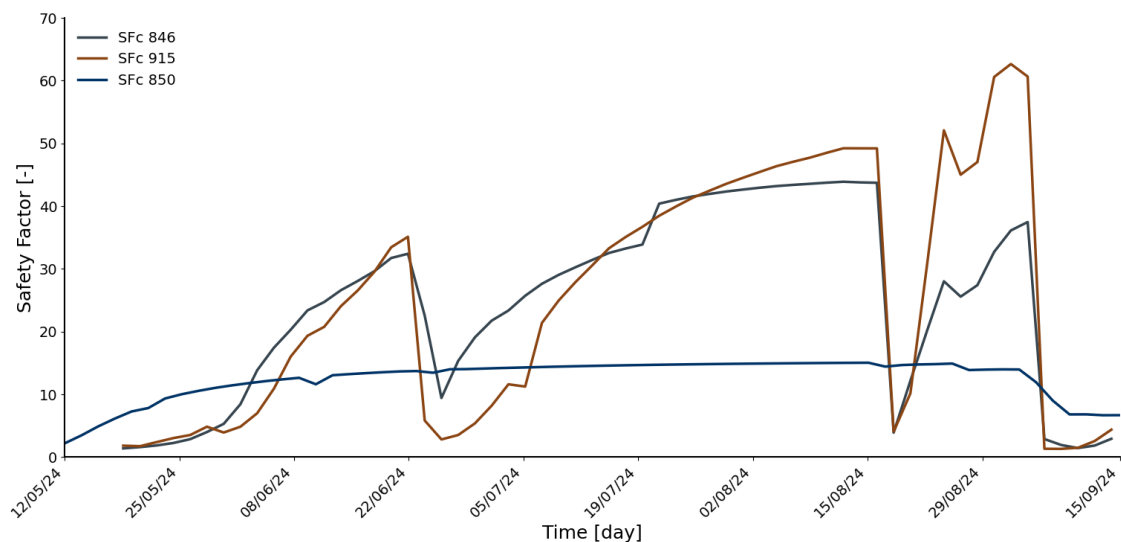


Figure 5.56 - Temporal variation of the factor of safety for the three experimental sites.

The analysis of the results confirmed previous observations: the influence of negative pore water pressures consistently ensures a safety factor (SF) above unity, even during the wetting phase, indicated that, under the hydrological conditions considered, all monitored sites maintained a stable condition. The relative variation of the safety factor between the different sites revealed a notable similarity in the behaviour of sites 846 and 915 throughout the entire hydrological cycle. These sites exhibited a high SF during the drying phase, consistently exceeding the values recorded at site 850. Conversely, during the wetting phase, sites 846 and 915 showed a lower SF compared to site 850, as by the temporal trend of the safety factor in relation to suction variation (Figure 5.57).

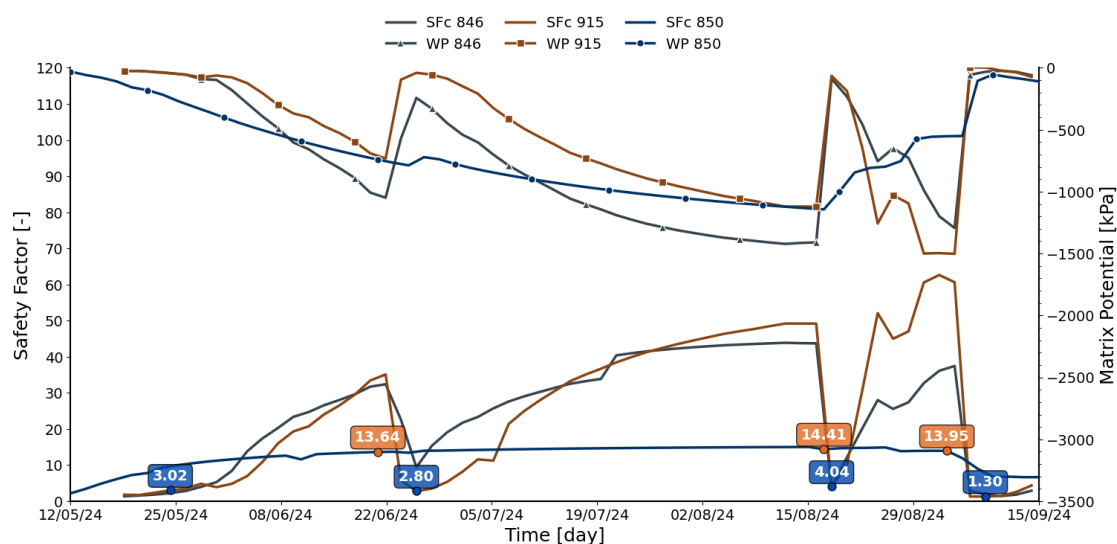


Figure 5.57 - Temporal variation of the factor of safety in relation to suction (the minimum SF values corresponding to the drying peaks are shown in orange, while those related to the wetting peaks are indicated in blue).

The graph shows a direct correlation between the effect of suction and the safety factor, highlighting that an increase in suction resulted in a corresponding increase in the safety factor, and vice versa. This comparison revealed that at Site 850 a lower sensitivity to variations in suction during the wetting phase compared to the other sites was found. Consequently, a nearly constant safety factor occurred across the transitions between different hydrological conditions. In Figure 5.57 the minimum values of the safety factor recorded at two distinct hydrological phases have been highlighted: drying periods (characterized by markedly negative water potential (Ψ) values) and wetting periods (where the water potential approaches zero). This differentiation made it possible to identify the sites that show the most critical stability conditions in response to changes in hydrological conditions.

Moreover, data revealed a differentiated trend in the safety factor. During the wetting phase, monitoring sites 846 and 915 showed the lowest safety factor values. This is directly correlated with lower negative pore pressure. In contrast, in the drying phase, the trend is reversed: site 850, despite having a negative pore pressure trend very similar to that of sites 846 and 915, recorded the lowest safety factor values.

To investigate in detail the factors that influence the variation of the factor of safety (SF) during the two phases of the hydrological cycle, several driving parameters were selected. These factors include both hydrological characteristics such as water content and suction and the geometrical properties of the slope, including cover thickness, inclination, and root depth.

The analysis was conducted by correlating the above-mentioned parameters with the SF values recorded during the periods of maximum drying (18/08/2024) and wetting (09/09/2024), which correspond to the minimum and maximum VWC values, respectively.

Moreover, the vertical variability of suction and VWC was taken into account. This variability is fundamental for a better understanding of the stability analysis results, particularly for the site 850. To this end, the mean values of suction and water content between the observation point (i.e., the sensor at 50 cm) and the deepest section of the downstream profile, where the flow analysis indicated higher pore pressure values, were examined.

Figure 5.58 illustrates the critical safety factor values recorded during the drying peak phase for the three investigated sites based on VWC and Ψ .

The most critical safety factor was found at site 850. This is consistent with the hydrological characteristics found this site, which exhibited the highest water content. The greater water content translates to a lower suction, which in turn decreases the effective stress and, consequently, the soil's shear strength.

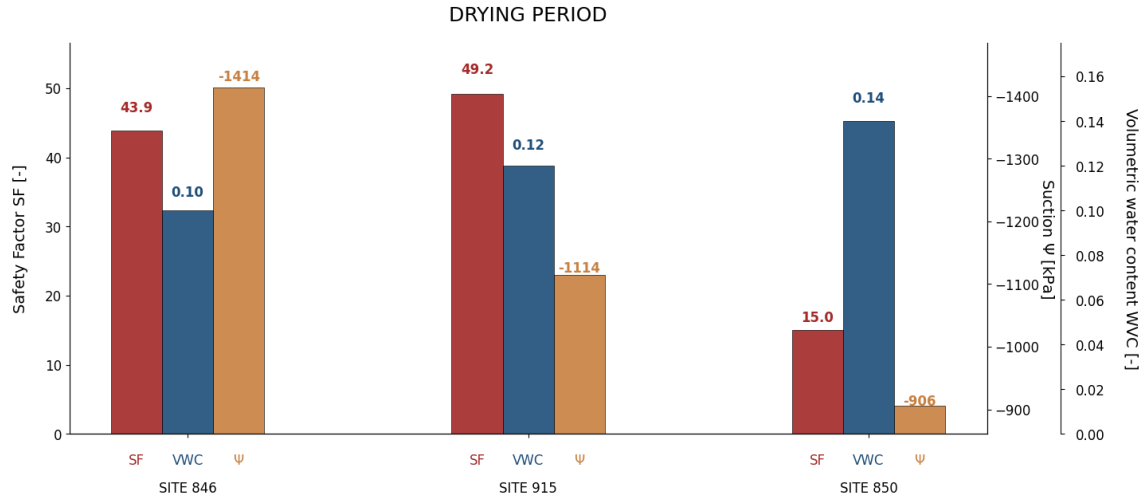


Figure 5.58 - Correlation between variations in the factor of safety at the three experimental sites with respect to volumetric water content (VWC) and suction (Ψ) during the drying period.

During the drying phase, the variation in suction is primarily controlled by the evapotranspiration process. This, in turn, is influenced by the type of vegetation, which affects both the evapotranspiration rate and the rooting depth. This depth is crucial as it determines the thickness of the soil layer affected by the stabilizing effects of suction (Figure 5.59).

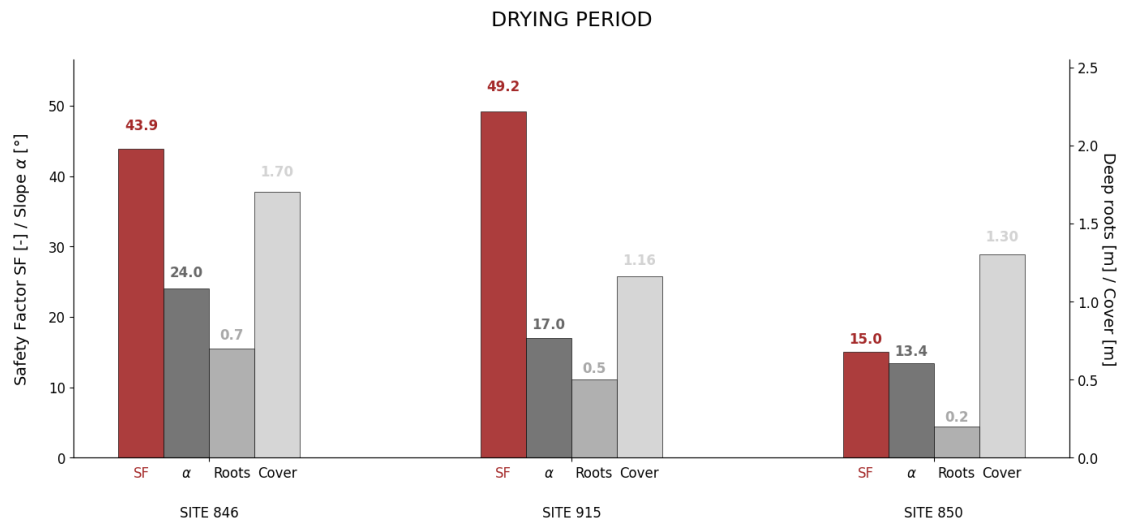


Figure 5.59 - Correlation between variations in the factor of safety at the three experimental sites with respect to slope inclination (α), cover thickness, and root depth during the drying period.

The comparison of the critical safety factor values with respect to root depths confirmed the previous findings (Figure 5.59). Site 850, resulting in the lowest safety factor during

desiccation, is characterized by shallow root depth, which in turn limits the stabilising effect of suction to only the shallowest soil layer.

At sites 846 and 915, the root depth distribution is almost uniform across to the soil profile (Figure 5.59). However, both the steeper ground surface and greater soil thickness play a critical role at site 846, leading to an increase in the shear forces acting along the potential slip plane and thus to a slightly lower factor of safety (Figure 5.59). The graphs depicted in Figures 5.60 and 5.61 revealed a different behaviour for all three sites during the wetting phase. Indeed, in this case the site 850 exhibited the greatest stability.

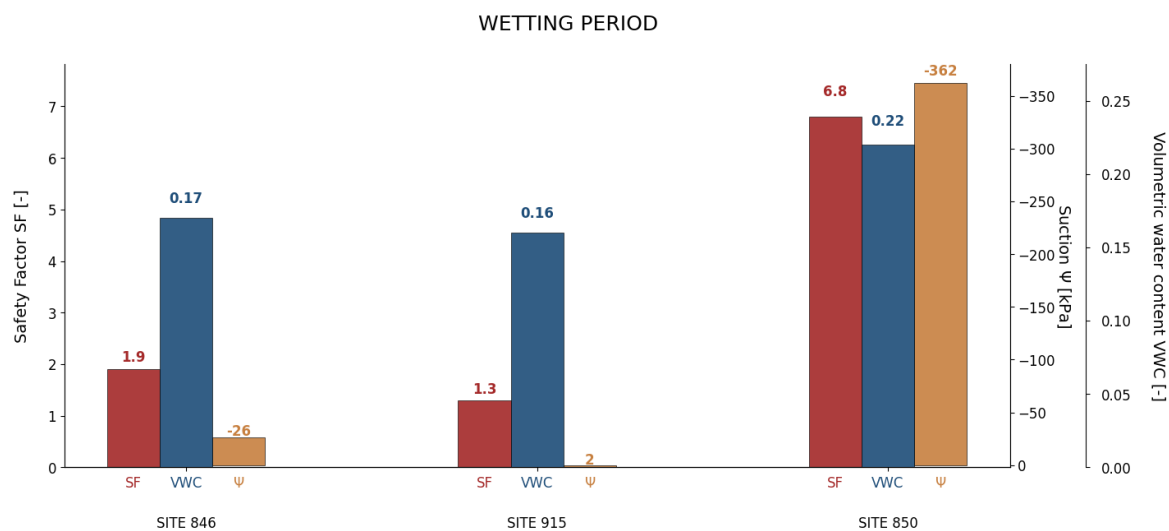


Figure 5.60 - Correlation between variations in the factor of safety at the three experimental sites with respect to volumetric water content (VWC) and suction (Ψ) during the wetting period.

During wetting, water content and suction are no longer controlled by evapotranspiration but by precipitation and the resulting infiltration. Consequently, the slope's stability depends on the soil's capacity to store and transmit water.

As previously observed (Figure 5.55), site 850 has a higher storage capacity. However, its low permeability slows down the water transmission to deeper layers, which are still affected by the previous suction conditions. This may explain the apparent inconsistency in the results since site 850 simultaneously shows a higher water content and greater suction compared to the other sites (Figure 5.60).

During wetting the variations in soil suction do not depend on evapotranspiration process or on the effect of the vegetative cover.

As illustrated in Figure 5.61, a direct correlation between root system depth and the factor of safety (SF) was not found. This phenomenon stems from the reduction or complete decay of the stabilising effect of cohesion, which is generated by root suction during the wetting phase. Given that the factor of safety is defined as the ratio of stabilising forces (i.e., cohesion, internal friction and effective stress) to destabilising forces (i.e., gravitational forces and slope), a reduction in the stabilising components necessarily increases the relative importance of the acting forces in the overall stability equation (eq. 40).

$$SF = \frac{c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)\tan\phi_b}{W\sin\alpha} \quad (40)$$

Since the three sites have the same friction angles and zero effective cohesion, an increase in pore pressure (u) reduces the effective stress ($\sigma' = \sigma - u$). In unsaturated soils, this phenomenon corresponds to a decrease in suction. This reduction in effective stress causes a decrease in resisting forces, making the slope's stability dependent on the acting forces, namely the slope's geometric features (inclination) and the soil weight, which in turn is a function of the soil thickness and of the profile length.

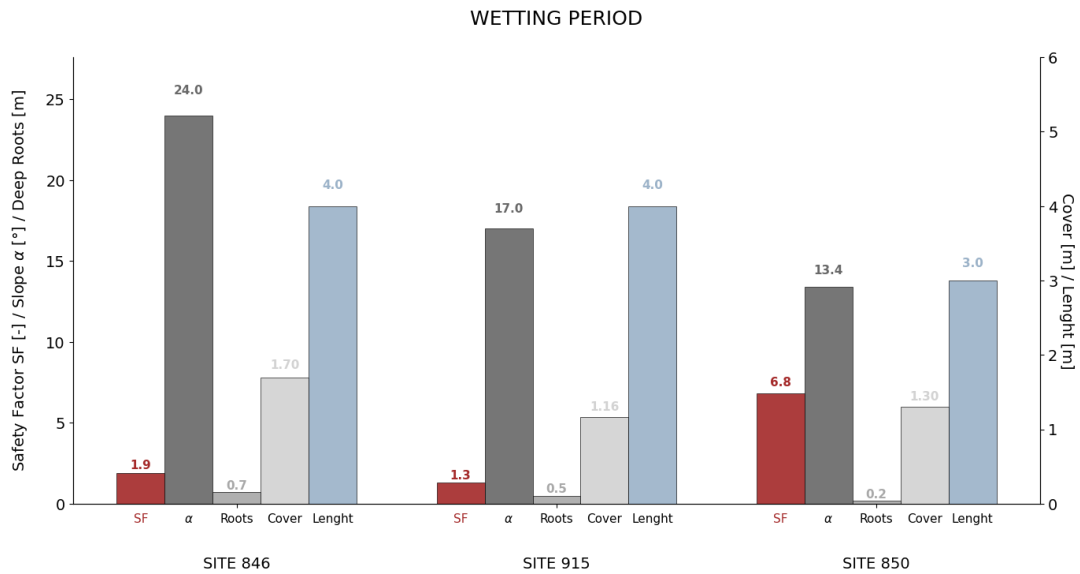


Figure 5.61 - Correlation between variations in the factor of safety at the three experimental sites with respect to root depth, slope inclination (α), slope length and soil cover thickness.

Based on a comparative analysis of the parametric relationships shown in Figure 5.61 the site 850 exhibits a higher safety factor. This can be explained by a more favourable balance between

the acting forces: the resisting forces are greater because of high soil suction, while the driving forces are lower. Specifically, the parameters that contribute to this reduction, namely the slope length and inclination along with the soil thickness are lower compared to other sites.

The lower safety factor obtained at sites 915 and 846 may be attributable to a higher slope gradient together with a greater soil thickness and slope length. On the other hand, the difference in the safety factor between sites 915 and 846, may stem from a smaller contribution of the resisting forces acting at site 915, thus giving a higher relative stability at site 846.

5.5 INVESTIGATION ON THE EFFECT OF HYDRAULIC BOUNDARY CONDITIONS

Previous local-scale analyses focused on examining the consequences of hydrological conditions on terrace stability. The objective now is to assess the effect of hydrological variations on the service behaviour of slopes, by using a finite element analysis via coupled flow-deformation analysis in PLAXIS 2D.; specifically, the intention is to simulate the evolution of the operating conditions of the dry-stone walls along a specific temporal sequence of drying and wetting cycles, in order to evaluate the trend of the total horizontal pressures originating within the soil-structure interaction zone.

The numerical analysis focused exclusively on Site 850 due to its in-situ instrumentation, which includes pressure cells installed at the back of the facing. This instrumentation played a crucial role by enabling a qualitative validation of the numerical model results regarding the total horizontal stresses exerted on the retaining structure.

Following the validation of the numerical model, by comparing pressure cells and water content/suction monitored data with simulation outcomes, the geometric configuration and intrinsic hydrological features of Site 850 were defined as the invariant reference scenario. This methodological approach aimed to isolate other main variables influencing the slope behaviour, thus allowing the analysis to concentrate on the detailed investigation of the role of vegetation. Therefore, by varying solely the evapotranspiration rate, representative of different vegetative conditions (condition "A" which refers to the real monitored scenario at the 850 site; condition "B" which refers to a cultivated slope, consistent with vegetation conditions detected at the 915 site), the change in the total horizontal pressures at the soil-structure interface was evaluated.

5.5.1 Numerical model setup: geometry and materials

Within the PLAXIS environment, the model geometry representing the Site 850 was defined (Figure 5.62) by also integrating a second layer, namely the bedrock.

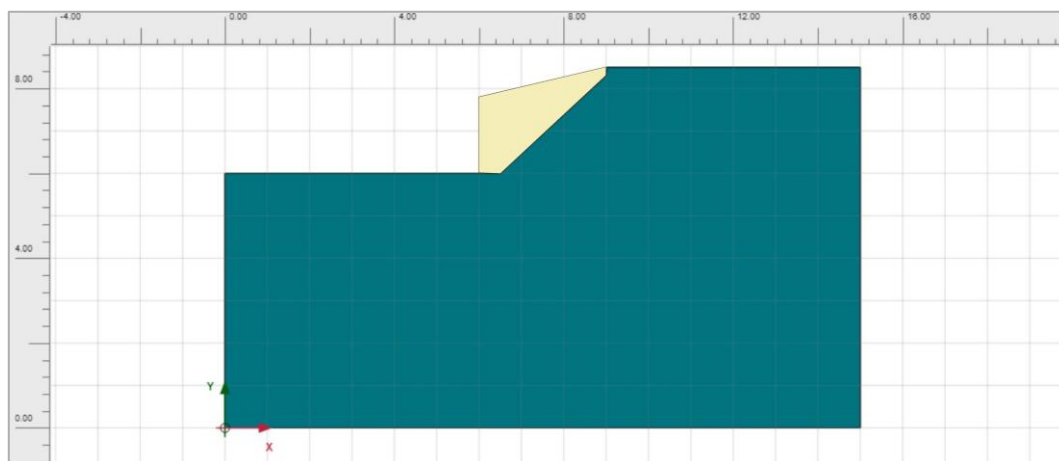


Figure 5.62 - Geometry of Site 850 reconstructed within the PLAXIS software.

For each material that characterises the model, its hydrological and mechanical properties have been defined (Table 5.15). These characteristics were organised into three main categories: General, Mechanical, and Hydrological. The General characteristics include the material's basic properties, the identification of the most appropriate constitutive model to represent the soil's behaviour, and the specification of its hydro-mechanical behaviour (analysis under drained or undrained conditions).

Table 5.15 – General properties related to the two materials.

GENERAL CHARACTERISTICS		
	Soil cover	Bedrock
Soil model	Mohr-Coulomb	Linear elastic
Material behaviour	Drained	Non-porous
Unsat. unit weight (kN/m ³)	16	23
Sat. unit weight (kN/m ³)	18	/
Porosity (-)	0,53	/
Void ratio (-)	1,1	/

To model the mechanical behaviour of the soil cover, an elasto-plastic approach was adopted using the Mohr-Coulomb constitutive model.

The bedrock was modelled with mechanical and hydrological properties chosen to minimise its interactions with the overlying cover layer. Consequently, the bedrock was treated as a quite

rigid constraint with linear elastic behaviour. This simplification, which minimises the mechanical and hydrological interactions, allowed to focus the analysis exclusively on the behaviour of the soil cover layer. Deformations and stresses induced in the bedrock were neglected. From a hydrological standpoint, the bedrock has been defined as a non-porous mean. This condition allowed to assume it as impermeable, acting as a hydrological barrier that limits infiltration, drainage, and the formation of pore pressure within it. Assuming the bedrock as a non-porous material, its specific weight is considered uniform and corresponding to that of a solid rock. This simplification reduced model complexity, allowing for a focus on the critical zones of interest.

The mechanical properties were defined by specifying the elastic moduli for each material and the strength parameters according to the adopted failure criterion (Table 5.16). The stiffness values, namely the Young's modulus and Poisson ratio, are derived from the data previously used for the global stability analysis (paragraph 4.2) while the friction angle was obtained from the results of the in-situ geotechnical tests.

Table 5.16 - Mechanical properties related to the two materials.

MECHANICAL CHARACTERISTICS		
	Soil cover	Bedrock
Young modulus (kN/m ²)	1,50E+04	1,50E+06
Poisson ratio (-)	0,3	0,2
Choesion (-)	/	/
Friction angle (°)	32	/

The van Genuchten model parameters and the saturated permeability values were specified allowing to automatically reconstruct the soil water retention curve and the function describing the variation of permeability in relation to suction (Table 5.17) (see section 3.3.5).

Given that the bedrock was modelled as a non-porous material, its hydrological properties were neglected in the analysis. The hydrological parameters used for the hydrological characterization of the model are derived from the previous hydrological modelling in GeoStudio (Table 5.17). In this regard, PLAXIS only require the van Genuchten parameters to automatically generate the water retention curve in terms of the degree of saturation.

Table 5.17 -Van Genuchten parameters reported in PLAXIS corresponding to the following classical curve parameters: $g_n = n$, $g_a = \alpha$ and $g_c = m$. K_x and K_y indicate the saturated permeability in the two directions.

HYDRAULIC CHARACTERISTICS	
	Soil cover
SWCC fitting model	van Genuchten
S_{res}	0
S_{sat}	0,72
g_n	1,28
g_a	0,3
g_c	$(1-g_n) / g_n$
K_x	3,50E-07
K_y	3,50E-07

The degree of saturation values was obtained by dividing the water content, derived from the GeoStudio analysis, by the material porosity.

5.5.2 Numerical model setup: retaining wall structure and mechanical properties

Once the site geometry and the mechanical and hydrological properties of the materials had been defined, the wall was incorporated into the modelling profile. The simulation purpose was to simulate retaining wall's mechanical behaviour, and specifically to determine the total pressures at the soil-structure interface. For this purpose, the wall was modelled using a "plate" element type.

The wall geometry was established by constraining its base to simulate its foundation. Two plate elements were anchored to this base: an inner plate element (Inner Wall), in direct contact with the soil, and an outer plate element (Outer Wall), positioned at a small distance from the first (Figure 5.63). These plates were then connected using a dense system of node-to-node anchors. This configuration was adopted because during periods of high suction the contraction of unsaturated soil tends to exert tension on the inner element, deforming it inwards and inducing displacements which are not physically meaningful, given the zero tensile strength assumed for the interface elements.

Consequently, the anchors connecting the inner wall to the outer wall were calibrated with low bending and shear stiffness to allow for deformation, but with specific mechanical properties: zero tensile strength and high compressive strength (Table 5.18). This design ensures that the entire lateral earth pressure generated by the soil is transmitted sequentially from the soil to the inner element, and from the inner element to the outer element, solely through the compression mechanism of the anchors.

In this way, the outer wall receives the actual total stresses generated during the interface compression phase (i.e., lateral earth pressure acting on the wall), while remaining unaffected by any inward interface tension during the soil contraction phase. Therefore, the model allows for both the estimation of the lateral pressure acting at the interface soil-retaining wall and the measurement of the outward horizontal displacements.

Summarizing, it was assumed that inward wall displacements are negligible, based on the hypothesis that soil contraction cannot exert tension along the wall-soil interface.

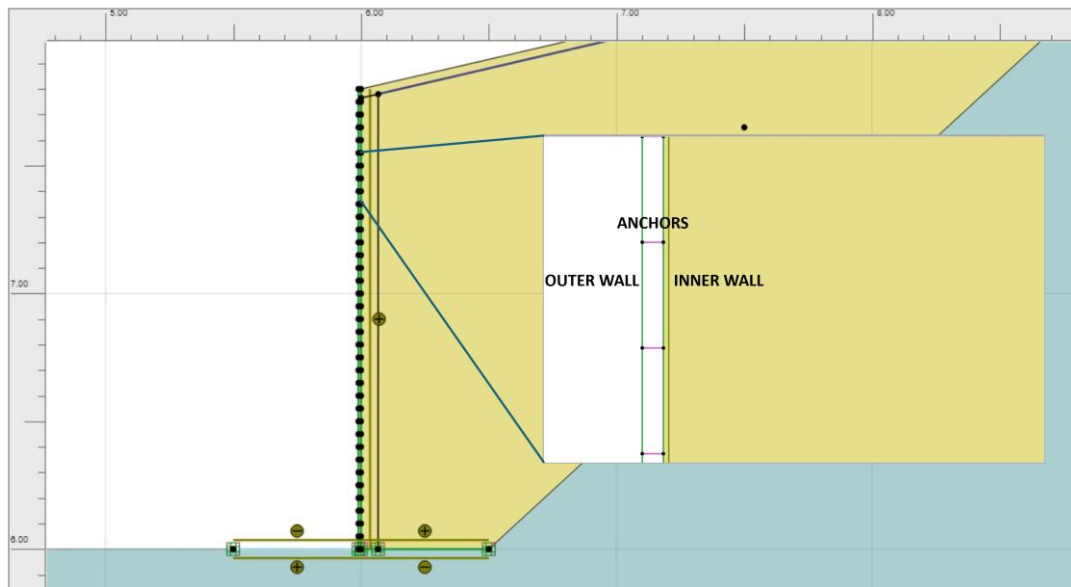


Figure 5.63 - Wall structural specifications: inner wall, outer wall and anchors.

Interfacing elements were introduced at the contact point between the structure and the backfill material. These elements are crucial for modeling the interaction between the structural element and the adjacent soil, as they enable a realistic simulation of a thin zone of material subjected to intense shear stress.

Once the geometry of the structure was defined, the mechanical properties were assigned to the plate elements. These properties are of fundamental importance as they allow for the definition of the element's self-weight (w), which is derived from the wall's dimensions, and the definition of the resistance and stiffness parameters, namely the flexural rigidity (EI) and the axial rigidity (EA). The general and mechanical characteristics, implemented in the PLAXIS software for modelling the plate elements and for the anchors are summarised in Table 5.18.

Table 5.18 – General and mechanical properties of the plate.

GENERAL CHARACTERISTICS		
	Wall	Anchor
Material type	Elastic	Elastoplastic
Weight (kN/m²)	12,5	/

MECHANICAL CHARACTERISTICS		
	Plate	Anchor
Axial stiffness (kN/m)	8,70E+05	1,00E-12
Bending stiffness (kN m²/m)	1,82E+04	/
Poisson ratio (-)	0,2	/
L spacing (m)	/	1
F max tension (kN)	/	0
F max compression (kN)	/	1,00E+12

The stiffness characteristics of the dry-stone wall have been assimilated to the elastic properties of well-laid, split-stone masonry. This is in accordance with the parameters detailed for this type of structure in the Italian technical standards for construction, which specify (in the context of a continuum mean schematization) an equivalent elastic modulus (E) of 1,750,000 kN/m² (Italian code DM January 17, 2018 (NTC 2018) and Circular 21 January 2019 n. 7). The plate was modelled with an elastic constitutive model. The self-weight per unit length of the structure, which acts on the ground, is calculated in the PLAXIS software as the product of the material's specific weight (25 kN/m³) and the plate's thickness (0.5 m) (values defined in Paragraph 2.5). The axial (EA) and flexural (EI) rigidities per unit length, on the other hand, were determined based on the well-established elastic formulations (41) and (42).

$$EA = E * d \quad (41)$$

$$EI \rightarrow I = \frac{b * h^3}{12} \quad (42)$$

In a two-dimensional model, d represents the wall thickness, while the parameter b, represents the out of plane dimension, conventionally set to 1 in a plane strain formulation (Megson 2019). The interface between the wall and the soil was modelled by considering a resistance reduction factor of 0.7 which reduces the soil's shear strength. This value (which is a common assumption for soil-structure interactions) indicates that only 70% of the soil's shear strength is considered.

R_{inter} value of 1 indicates a full preservation of strength at the interface (equal to that of the surrounding soil), while an R_{inter} equal to 0 represents a frictionless and cohesionless interface.

5.5.3 Numerical model setup: boundary conditions and mesh

With regard to the hydrological boundary conditions, open boundary conditions were defined along the model lateral boundaries. The upper boundary of the cover is similarly an open hydrological boundary where a prescribed hydraulic head flux is imposed. This allows for both inflow and outflow from the system, depending on the prevailing hydrological conditions. The specific application of this load and its detailed characteristics will be fully illustrated within the context of the coupled analysis (as described in Paragraph 3.5.4).

Regarding the mechanical boundary conditions, a fully fixed constraint was applied along the lower YY' segment (the model base), which prevents any movement or rotation. This condition imposes that all displacements and rotations are zero. The upper boundary of the model (the upper YY' segment) is unconstrained and therefore free to move in any direction. Finally, normally fixed boundary conditions were defined to laterally constrain the domain, preventing displacement only in the direction normal to the boundary. This permits movement only in the vertical direction, blocking horizontal displacement ($u_x=0$).

As PLAXIS is a finite element software, it was necessary to define a finite elements mesh. The mesh dictates the detail and accuracy of the analysis through the size of its elements and the number of nodes, where the coupled problem, defined by a set of partial differential equations, is numerically solved (Zienkiewicz et al. 2005). For this analysis, a six-noded triangular elements mesh was used. The choice of six-noded elements, rather than the simpler three-noded elements, allows for a more accurate description of the material's behaviour, as the shape functions (Zienkiewicz et al. 2005) used for interpolation are of a higher order (i.e. quadratic). The governing equations of the problem are solved at the mesh nodes, yielding an approximate solution for the field of physical quantities under examination.

To optimise the trade-off between result accuracy and computation time, a non-uniform meshing strategy was implemented. The mesh density was increased (with smaller elements and, consequently, a higher number of nodes) in areas of greater interest, namely in proximity to the filtration surface and the retaining wall. This choice is justified by the expectation of a high gradient in both stress/strain and hydraulic flow in these critical zones. A marked gradient indicates a rapid and significant variation of the problem's variables, making a finer discretisation essential to accurately capture their behaviour. Conversely, in areas more distant

from the constraints and boundary conditions, the mesh was kept coarser to reduce the total number of nodes and, consequently, processing times (Figure 5.64). Overall, 2242 nodes and 962 six-node elements were defined.

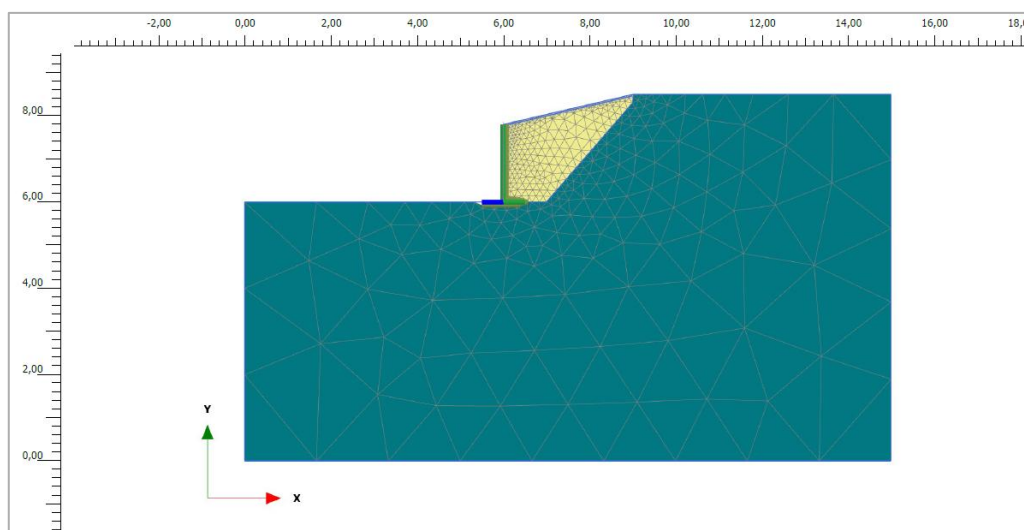


Figure 5.64 - Mesh geometry and node distribution.

5.5.4 Numerical model setup: detailed description of the analysis phases

The simulations conducted in PLAXIS began with calculation of the initial geostatic stresses of the soil (both vertical and horizontal) based on the materials' self-weight and geometries and defined the hydrological initial conditions according to the model configuration.

Accordingly, a first “Initial Phase” analysis was executed, allowing for the definition of the initial geomechanical and hydrological conditions upon which the subsequent coupled flow-deformation analysis was developed. Table 5.19 details the main characteristics set for the Initial Phase and the subsequent coupled flow and deformation analyses.

Table 5.19 – Description of the main simulation phases

Phase	Description	Calculation type	Pore pressure calculation type
0	Initial condition	Gravity loading	Phreatic
1	Drying phase	Fully coupled flow -deformation	Steady state groundwater flow
2	Wetting phase	Fully coupled flow -deformation	Steady state groundwater flow

- **Initial phase**

The initial geostatic stress state of the model was determined through a gravity loading analysis. This method, whose theoretical treatment is outlined in Paragraph 3.3.5, constitutes a static analysis aiming to calculate the distribution of internal stresses by simulating the application of the material self-weight, starting from an initial condition of zero stress. During this preparatory phase, a specific initial hydrological condition was defined for the model's cover. This condition was set as unsaturated, with a degree of saturation equal to 0.64. This numerical value reflects the starting hydrological state of the soil, representing the degree of saturation actually present at the beginning of the selected modelling period for the analysis.

For the gravity loading analysis (Table 5.19), the calculation of pore pressures was specifically set to the phreatic mode. This setting simulates a condition of hydrostatic equilibrium. It should be noted that, at this initial stage, no external loads were applied to the system.

- **Fully coupled analysis**

Based on the geostatic and hydrological conditions defined in the initial phase, a coupled flow-deformation analysis was performed. The theoretical principles of this methodology were detailed in Section 3.3.5. Unlike the previous analysis, this one is transient in nature, allowing for the assessment of the mechanical and hydrological parameters over time.

Prior to commencing the analysis, the accumulated strains from the preliminary phase were reset to zero. The maximum limit for the number of time steps was set at 10,000, thus small loading steps were adopted to ensure convergence of the complex coupled problem throughout the entire time interval, allowing the gradual attainment of equilibrium. Given the substantial computational burden of the problem and the extensive duration of the study period, in order to effectively visualise the evolution of horizontal stresses in the soil at distinct time intervals during the simulation (from 02/05/2024 to 15/09/2024), it was decided to subdivide the overall analysis period into discrete 14-day intervals (as detailed in Table 5.20). This fractionation ensured both the optimisation of computational resources and a higher efficiency in the subsequent phase of interpreting the analytical results.

Table 5.20 – Characteristics of the fully-coupled analysis.

Phase	Description	Calculation type	Load history	ΔTime (s)
Drying phase	Phase 1	Fully coupled flow -deformation	P_drying period ET_drying period	1,21E+06
	Phase 2			1,21E+06
	Phase 3			1,21E+06
	Phase 4			1,21E+06
	Phase 5			1,21E+06
	Phase 6			1,21E+06
	Phase 7			1,21E+06
Wetting phase	Phase 8	Fully coupled flow -deformation	P_wetting period ET_wetting period	1,21E+06
	Phase 9			1,21E+06
	Phase 10			9,50E+05

The analysis is therefore articulated in ten distinct phases, grouped into two macro-groups based on their hydrological period: the Drying Phase and the Wetting Phase. Each of the ten phases is characterised by a specific time interval that defines its duration. Nine out of the ten phases exhibit a uniform time interval of 1,21E+6 (14 days), while the final phase is the sole exception, characterised by a time interval of 9,50E+5 seconds (11 days).

In a fully coupled flow–deformation analysis, the solver works with the total pore water pressure, i.e. the combination of steady-state and excess components. For consistency with other calculation types, the steady-state field is calculated based on the hydraulic conditions at the end of each phase, and the excess pore pressures can be inferred via back-calculation from the total pore water pressure response. To accurately model the hydrological phenomena, time histories of precipitation and evapotranspiration were assigned to the top boundary of the domain. The adopted technical solution allowed the application of the two distinct flux vectors (inflow/outflow) required for the hydrological simulation. Since infiltration (inflow) and evapotranspiration (outflow) act in opposite directions, two adjacent boundary lines were introduced, each assigned with its own flux history. These lines were placed at a small but finite distance, consistent with the characteristic length of the mesh and the problem scale, in order to pursue numerical stability at the same time. This geometric arrangement allowed the model to correctly handle the two distinct flux components without ambiguity in the flow direction. The loading histories implemented in the model refer to those already used in the previous analysis and described in Section 5.2, in order to simulate the hydrological period between 02/05/2024 and 15/09/2024.

In the PLAXIS software, hydraulic flux entering and exiting the system is defined in terms of discharge per unit area, denoted as "Δ Discharge" and measured in cubic metres per second

(m^3/s). Consequently, the rainfall and evapotranspiration values used in the previous analyses, which were originally expressed in metres per second (m/s), were converted into discharge rates. To achieve this, these values were multiplied by the length of the area of interest and by the third dimension, which is considered unitary in a two-dimensional (2D) plain strain model. Unlike GeoStudio, which allows the Potential Evapotranspiration (PET) to be automatically corrected as a function of the matric suction, PLAXIS does not provide a similar feature. Given the already high computational complexity of the fully coupled analysis, the PET boundary condition was therefore treated as a parametric input. The baseline (zero reference) of the PET time history was defined through calibration, ensuring that the simulated water content and suction trends matched the observed field behaviour (Figure 5.65). For the subsequent Model “B”, which accounts for a change in vegetation cover (consistent with site 915) and the resulting increase in evapotranspiration, the same calibrated baseline was retained, and the new PET function was introduced as an offset of Model “A”. This approach was adopted to ensure consistency between the two scenarios and allowed the comparison to isolate the sole effect of vegetation-induced evapotranspiration variations.

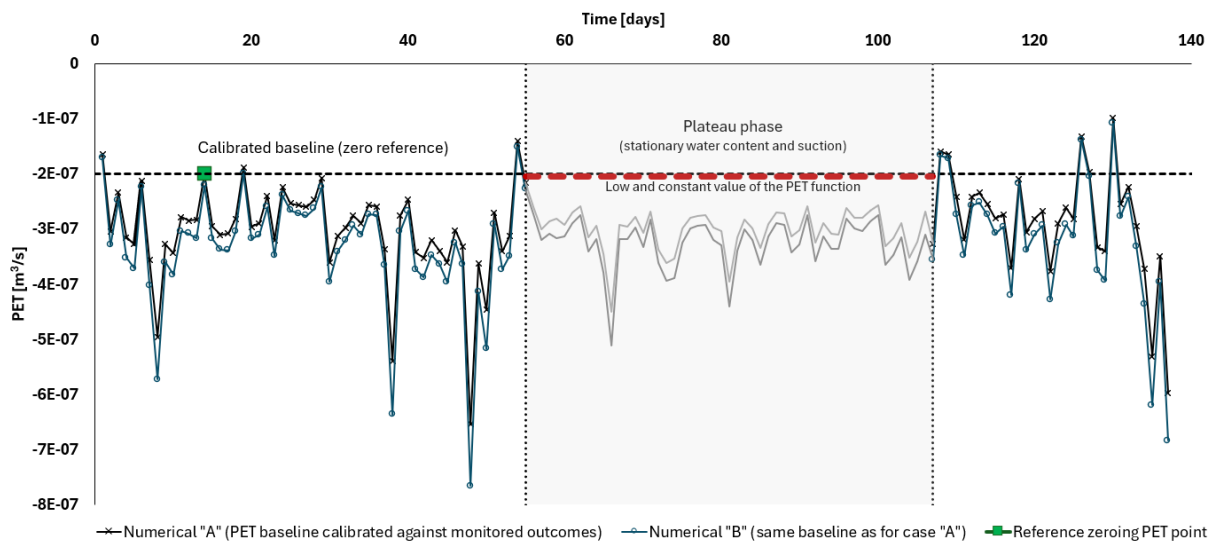


Figure 5.65 – PET function calibration.

A low and constant evapotranspiration value ($5\text{E}-9 \text{ m}^3/\text{s}$) was manually calibrated during the stationary period between 25/06/2024 and 17/08/2024 (numerical phase 5, 6 and 7, see Table 5.20), referred to as "plateau" phase (Paragraph 5.1.4), to match the field measurements. During this period, the suction and water content sensors remained almost constant, and no precipitation occurred.

The choice of a low and constant evapotranspiration value accounts for a limitation of PLAXIS: once the soil becomes completely desaturated, the subsequent re-saturation through infiltration cannot be reproduced due to the monotonic, non-hysteretic form of the water-retention model (Pradhan et al. 2022).

Observation points, consistent with field monitored points, were incorporated into the numerical model to facilitate the validation of simulation results. Specifically, the configuration of the observation points was defined as follows: two observation points were placed behind the wall (both internally and externally to its structure) at two distinct elevations relative to Ground Level (GL = 1.8 m): 0.8 m and 1.6 m. These elevations were selected as they are representative of the installation heights of the pressure cells used for the field measurements. Furthermore, an additional observation point was set at a depth of 0.50 m below the ground surface, in the middle of the terrace geometry. This depth corresponds precisely to the field installation level of the suction and soil moisture sensors, thereby ensuring a direct and meaningful comparison between the model's predictions and the experimental measurements.

5.5.5 Numerical model results: validation and role vegetation

The results from the coupled flow-deformation analysis for the site 850 indicated a satisfactory agreement between the simulated (Numerical) and observed (Monitoring) data for the key hydrological parameters. Specifically, for what concerns the water content, the simulation reproduces the concave trend and the seasonal variation, capturing the minimum content (peak aridity) observed in mid-July. Correspondingly, for suction values, the numerical curve models the convex trend, intercepting the suction peak during the same summer period. (Figure 5.66).

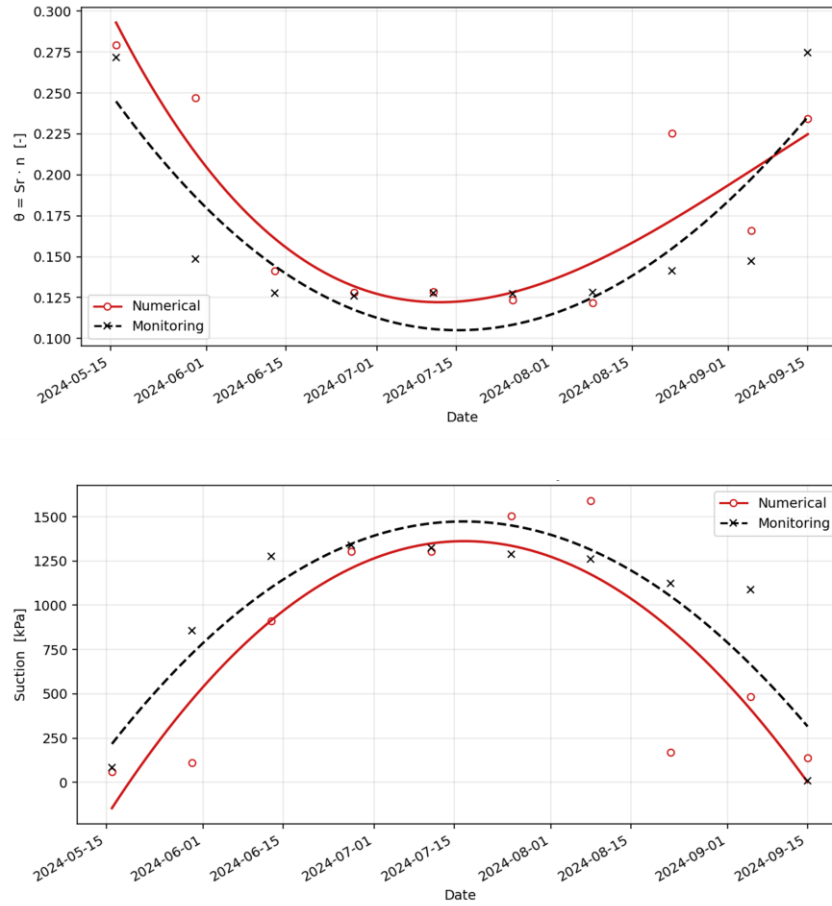


Figure 5.66 - Comparison of the simulated water content and suction data with the recorded monitoring data.

In the following section, the simulation results, expressed as total horizontal stress acting along a vertical section close to the retaining wall, are compared with the pressure data recorded by the field instrumentation. This comparison was conducted with the objective of assessing the coherence of stress evolution induced by the drying and wetting cycles, rather than to achieve a direct quantitative match (see Section 5.1).

To address the aforementioned limitations, the comparison was developed in terms of normalized quantities. This methodological approach enabled the comparison of the relative evolution of the investigated quantities and permitted the qualitative validation of the numerical model performance. The normalization procedure was applied separately to both the monitoring data and the numerical results, following the identical methodology in both instances.

For each pressure cell location (i.e., CP03 and CP04), the time series was centred with respect to its mean value and scaled by half of its peak-to-peak amplitude, as determined by the maximum and minimum values recorded within the selected period. Consequently, the normalised series spans the interval $[-1, +1]$ (Figure 5.67). The same procedure was

subsequently applied to the numerical model but using the maximum and minimum values of the total horizontal stresses predicted at the corresponding CP03 and CP04 locations. Hence, in both the monitoring and modelling contexts, normalisation is executed with reference to the maximum observed values at the points of interest, while maintaining independence between the field and numerical values. The result of this approach is that the normalised time series derived from both the monitoring and the numerical simulations in CP03 and CP04 vary within the common range of $[-1, +1]$. This facilitates a direct comparison of their temporal trends, irrespective of any absolute offsets or differences in magnitude.

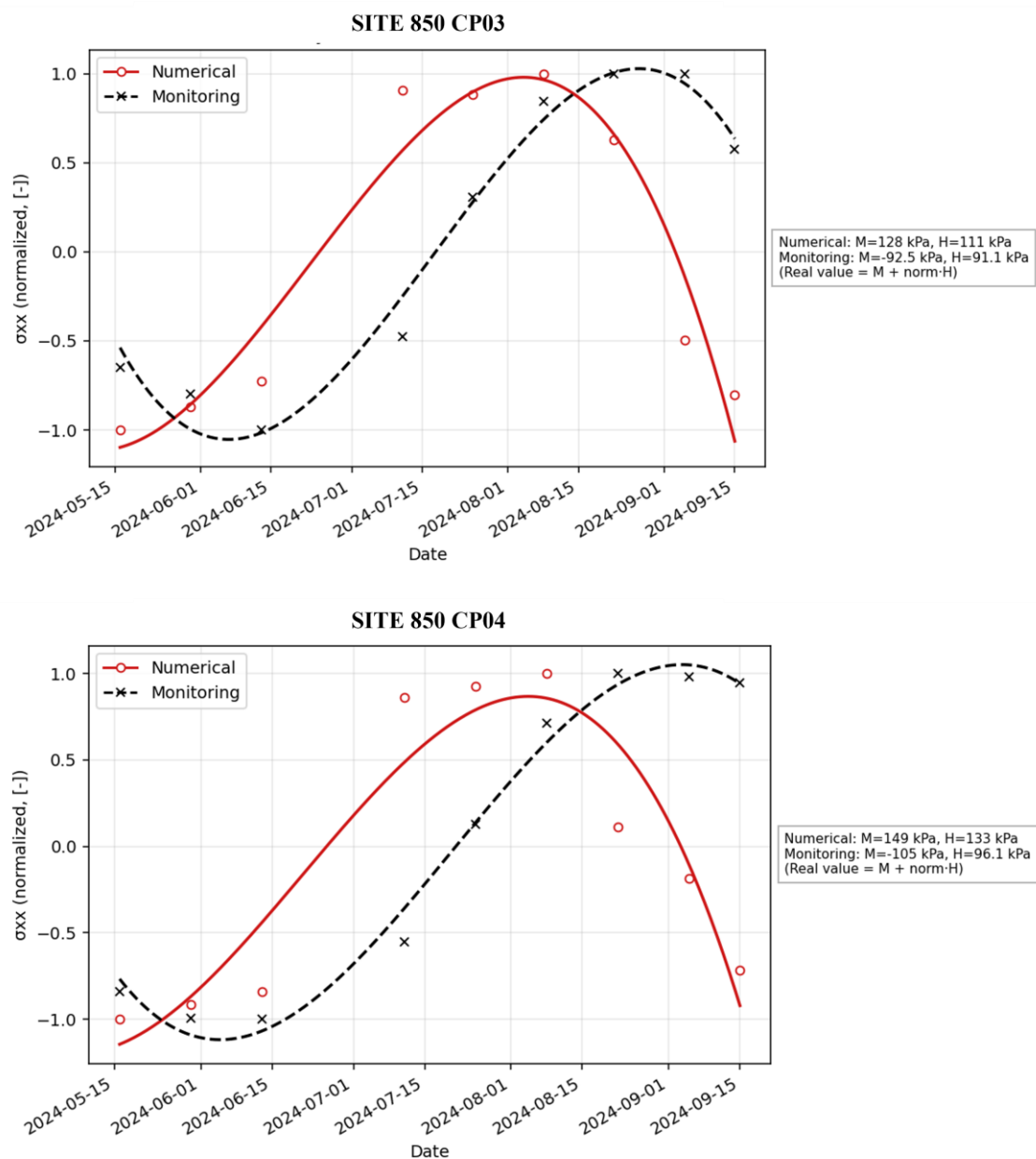


Figure 5.67 - Comparison between the normalized results of horizontal pressures measured by monitoring data and those derived from the simulation.

The results of the analysis confirm a satisfactory agreement in the evolutionary trends between simulated and observed data. Notwithstanding the coherence in the evolution of the variables, a systematic temporal lag has been observed within the comparison. This temporal discrepancy constitutes a phenomenon that has been previously identified. Indeed, as documented in the data analysis in Paragraph 5.1, a similar time shift was observed in the comparison between data derived from hydrological monitoring and those recorded by the pressure cells. The hypothesis initially formulated in that context attributed the genesis of this phenomenon to speed soil infiltration processes.

However, a detailed examination of the results from the current simulation necessitates a re-examination of this hypothesis, since it shows coherence between total stresses and hydrological quantities variation across the time interval considered (no substantial delay observed within the numerical domain). Given that this variation trends agree with the hydrological data measured in situ by the field sensors, it is deduced that the monitored temporal lag between pressure cells and hydrological quantities variations cannot plausibly be ascribed to the intrinsic speed of infiltration processes.

These outcomes suggest an alternative hypothesis regarding the origin of the systematic delay encountered within field measurements (pressure cells readings vs. measured hydrological quantities): this might be attributable to a problem linked to the installation phases, specifically adhesion defects or interference phenomena between the pressure cell, the adhesive mortar used, and the surrounding ground. Nevertheless, the proposed hypothesis cannot be conclusively validated due to the lack of direct evidence supporting this mechanism.

The observed delay is further illustrated through a representation method that divides the monitoring period into ten 14-day phases, comparing normalized pressure-cell readings (blue lines) with normalized numerical total horizontal stresses (red curves) along the soil-structure interface (Figure 5.68).

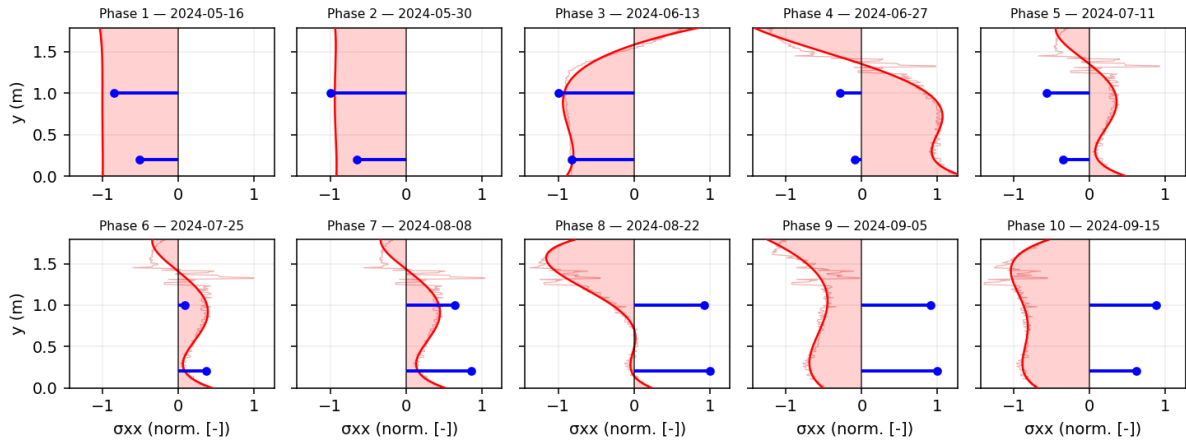


Figure 5.68 - Comparison of normalized numerical total horizontal stresses resulting from numerical simulation and normalized pressure-cell field readings, segmented by time periods (numerical model phases).

Following the validation of the coupled hydro-mechanical model for Site 850 (model “A”), attention focused on isolating and quantifying the exclusive influence of vegetation on total horizontal stresses. To ensure the isolation of this effect, the analysis was conducted by keeping the system's geometry and the soil's intrinsic hydrological characteristics constant, concentrating the variation solely on the evapotranspiration (ET) loading history, as previously described. Therefore, a variated configuration for site 850 was parametrically investigated, by considering cultivated vegetation (Model “B”), which induces the maximum aspiration and, consequently, the maximum soil suction. These two configurations (“A” and “B”) were compared with a fully saturated condition, in terms of water content, suction and total horizontal stresses at the interface soil-retaining wall (Figure 5.69 and 5.70).

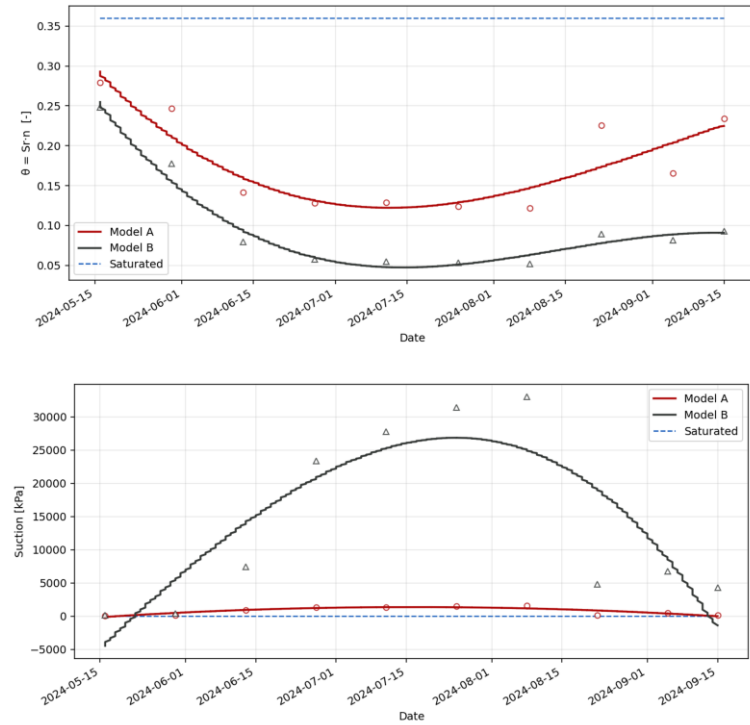


Figure 5.69– Water content (upper) and suction (lower) at SM02 point within the selected time frame - Comparison between unsaturated numerical models (A-B) and saturated condition

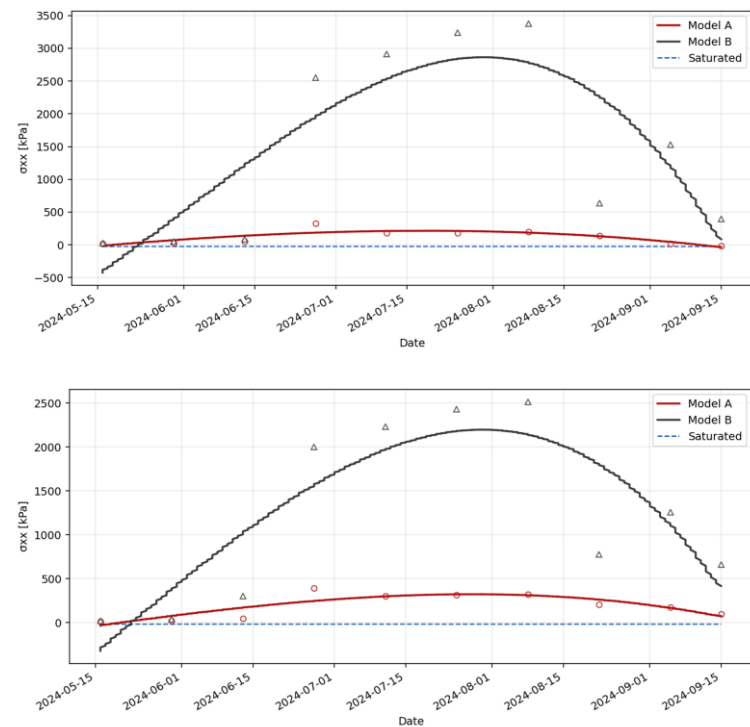


Figure 5.70 – Total horizontal stress at pressure cells CP03 (upper) and CP04 (lower) within the selected time frame - Comparison between unsaturated numerical models (A-B) and saturated condition

Comparative analysis shows that Model “B,” characterized by lower water content, develops higher matric suction. This condition reduces the soil void ratio (Huat et al. 2005) and shifts the total horizontal stresses toward positive values (no pressure acting on the wall). The stresses peak during the drying phase and decrease upon wetting, indicating a suction-dominated, stiffening state with no active pressure acting on the retaining wall. Conversely, in a complete saturation scenario, the total horizontal stress values reflect an active pressure exerted on the retaining wall, as expected. Within the framework of these two investigated limiting states, the hydro-mechanical conditions recorded at Site 850 (Model “A”) occupy an intermediate position.

In order to conduct a systematic evaluation of the variation in total horizontal stress (σ_{xx}) occurring at the interface between soil and retaining wall, as a function of the three distinct land-use conditions and in correlation with the various phases of the hydrological cycle, the overall analysis period was discretised into ten temporal phases.

Thus, Figure 5.71 illustrates the evolution of the total horizontal stress (σ_{xx}) profiles with respect to depth (y) over a temporal interval that includes a distinct drying phase (Phases 1–7) followed by a subsequent wetting phase (Phases 7–10), showing the three conditions investigated.

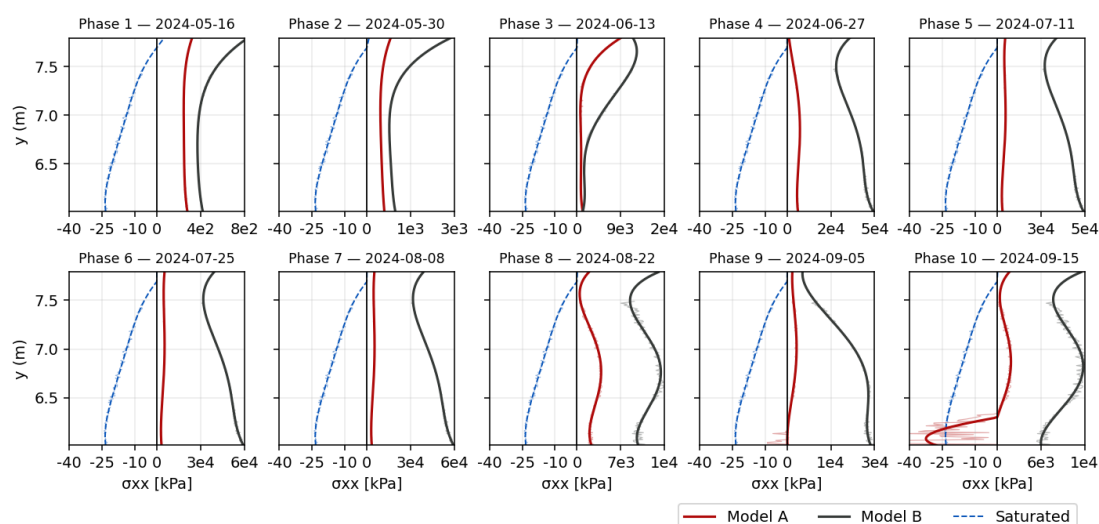


Figure 5.71 - Variation of the horizontal stress exerted by the soil on the wall, considering three different land use conditions.

It is assumed that the "saturated" condition represents the “baseline behaviour”, indicating a roughly linear evolution of soil pressure with depth acting on the wall, with values ranging between 0 and -25 kPa. The comparative analysis focuses on evaluating and contrasting to this “baseline behaviour” the total horizontal stresses developed at the soil-structure interface with

Model “A” and Model “B” during the different phases of the hydrological cycle, in order to discern the differences in mechanical response induced by variations in saturation and water content. In the initial drying phases (Phases 1-3), both models, A and B, exhibit a suction-dominated regime (with stiffening of the soil response, Rotisciani et al. 2021) characterized by positive and almost equivalent horizontal stress values. These values progressively increase concurrently with the advancement of the evapotranspiration process. From Phase 4 up to the peak drying condition (Phase 7), a marked divergence is observed between the models: Model “B” reaches significantly high positive suction values, while Model “A” shows a less substantial increase. Nonetheless, both models remain in a suction-dominated regime, with no pressure acting on the retaining wall. With the onset of the wetting period (Phase 8), the total horizontal stresses at the interface for both models begin to decrease, with reductions potentially reaching an order of magnitude. This trend continues throughout the wetting phase until it reaches its peak. At the peak wetting phase, the Model “A” experiences a regime inversion: the total horizontal stresses become negative at the base, indicating a gradual transition towards the saturated regime, with pressure acting on the retaining wall. The maximum total horizontal stress values, particularly recorded at the base of the wall, reach a peak of approximately -25 kPa. Model “B”, conversely, despite registering a significant reduction in positive total stress values compared to the drying phase, persists in a suction-dominated regime with no pressure acting on the wall. Based on the analysis of the stress regimes, it can be deduced that, given the same geometric configuration and soil hydrological conditions, the intervention of cultivated vegetation (Model “B”) imparts greater stability to the slope compared to a condition of short-term agricultural abandonment or, more drastically, a situation implying the complete removal of the vegetative component from the terrace surface (Saturated). The persistence of Model “B” in a suction dominated regime, even during the critical wetting phase, ensures the absence of active pressure on the structure, which nevertheless is a determining factor for the stability of the slope-wall system as well.

It is important to notice that, although high matric suction increases stiffness and strength in the unsaturated zone (Tarantino & Di Donna 2019), the suction-induced deformations (e.g. wetting-induced volumetric compression) must also be considered. Indeed, subsequent wetting may trigger wetting-induced volumetric compression (“collapse”), so the beneficial effect of suction is not unconditional (Dumont et al. 2010). As a matter of fact, PLAXIS with standard Mohr–Coulomb cannot capture wetting-induced collapse as a suction-driven plastic mechanism. Furthermore, beyond certain suction levels, further mechanical benefits may diminish, and capillary stress reaches a horizontal asymptote (Dumont et al. 2010).

DISCUSSIONS

The central objective of this research was to quantify the factors that influence slope stability on terraced hillslopes through an integrated multiscale analysis. This goal was achieved by combining hillslope-scale stability analyses with terraced-scale detailed investigations focused on quantifying water circulation dynamics. To this end, robust hydrological models were employed, the validity of which was ensured by rigorous processing and quantitative validation of hydrological monitoring data. The accurate representation of hydrological circulation within the studied slopes allowed for i) assessing the influence of different land-use configurations on pore-water pressure regimes; ii) analysing pore-pressure variation in influencing slope stability and iii) investigating the soil-structure interaction using coupled numerical models, which enabled the reconstruction of horizontal stress variations on the retaining wall as a function of specific hydrological conditions and different land-use configurations.

These interpretations were conducted starting from a global stability analysis (i.e., strength reduction analysis), which concerned the entire slope encompassing all three sites. The analysis was set up taking into account the specific peculiarities of each site, thus including the different slope geometry and stratigraphy, the mechanical characteristics of the material underlying the wall foundation, and the effect of apparent cohesion provided by the different vegetative conditions.

The investigation highlighted how geometry and stratigraphy can contribute significantly to the stability of terraced slopes. However, it was found that the primary element potentially conditioning slope failure, both in terms of spatial extent and event magnitude, is attributable to the mechanical characteristics of the material upon which the retaining structure is founded. The analysis revealed that where the wall structures are predominantly founded on the soil cover or highly weathered rock mass, a much more critical instability condition were found. This marked instability can persist despite a greater root cohesion. In these cases, the greater soil thickness on the upslope sides along with poor mechanical properties of the ground where walls are founded can generate acting forces that are too substantial to be counteracted by the contribute of apparent cohesion. Conversely, along the slope segments where the walls rest on the bedrock, instability mechanisms tend to be localised at the individual terrace-dry-stone-wall system.

In the sites where the retaining structures rest directly on the bedrock, the overall analysis demonstrated greater global stability due to a higher mechanical resistance of the foundation

material. In these contexts, any potential instability tends to be localised and circumscribed to the individual dry stone-wall terrace system.

The conditions that lead to such local instability phenomena can no longer be primarily attributable to the foundation structure of the retaining work, but they can be correlated with a series of local factors. These factors can include the apparent cohesion conferred by the root systems, the site's hydrological dynamics (i.e., storage capacity, permeability) and the specific local geotechnical and geometric characteristics of the single terrace-wall element. Therefore, in these cases, the assessment of instability dynamics should better focus on the role of these factors at a detailed scale (Figure 6.1).

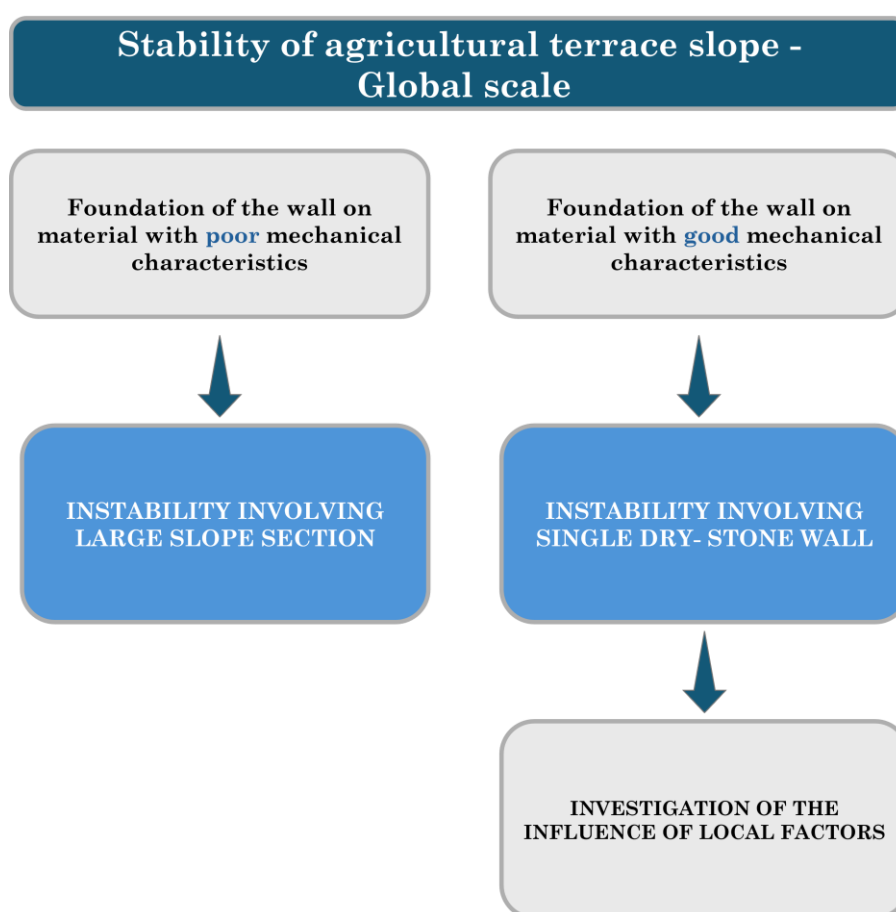


Figure 6.1 - Summary of global-scale stability analysis results.

Detailed analyses on individual terrace-dry stone wall systems considered representative of the three experimental sites were undertaken to gain a better insight on the local dynamics of slope instability.

To this end, the acquired monitoring data were used to reconstruct hydrological models for each of the three experimental sites. To this purpose, the whole monitoring dataset was preliminary

subjected to a rigorous data quality assessment, which substantially confirmed their reliability. The main critical issue concerned the wind speed measurement, for which a rectification procedure was carried out on some values deemed physically inconsistent. The corrected values were subsequently compared with data from an adjacent weather station to ensure the validity and coherence of the rectified data. A second issue arose from the total pressure cells, whose recorded data were considered in qualitative terms. This limitation is likely dependent on the wide measurement range of the sensors, which affected their ability to accurately and precisely capture the absolute values of the total stresses acting on the wall. A further issue arose from the comparison of these measurements with those recorded by hydrological sensors, revealing a systematic delay in the signal registration by the pressure cells.

Following validation, the analysis of hydrological monitoring data allowed for the construction of the WRC and the assessment of relative permeability (k_{rel}), which were subsequently used to validate the hydrological model and to investigate the hydrological dynamics affecting the study sites. Specifically, the procedure involved the application of load histories relating to both precipitation and evapotranspiration processes. This is crucial to describe the soil hydromechanical behaviour, enabling the quantification of the varying hydromechanical contribution that different vegetation types provide to the soil at each site. The evapotranspiration rate for each experimental site was accurately determined using the Penman-Monteith equation, based on meteorological data and the specific vegetation characteristics.

The results derived from the construction of the hydrological model allowed for a significant differentiation in the hydrogeological behaviour of the investigated sites. Site 850 exhibited a high-water retention capacity, particularly at low suctions. However, this capacity is counterbalanced by a reduced permeability, especially at higher suctions, which limits its effectiveness in transmitting water down the soil profile (Figure 6.2). This peculiar hydro-physical combination fosters the formation of a persistent “waterlogging” in the surface layer of the soil.

This greater capacity to retain water in the surface layer may be directly correlated with a higher Organic Carbon (OC) content. The presence of spontaneous grass also concurs to promote the accumulation of organic matter through two principal mechanisms: the existence of a dense, shallow root network that provides a continuous and substantial input of biomass and the absence of mechanical tillage, which prevents soil oxygenation and the consequent accelerated microbial decomposition.

The low permeability detected at Site 850, especially under conditions of high suction, has been attributed to the grain size distribution of the soil. It was hypothesised that the soil sieving

undertaken during construction of the terrace embankment may have led to an increase in the proportion of fine particles. This composition presumably resulted in a predominantly homogeneous pore distribution, characterised by predominantly small and medium pore sizes. This structural uniformity, confirmed by the absence of a double porosity water retention curve, indicates the absence of significant macropores. Based on these considerations, it was deduced that this almost uniform distribution of capillary pores generated the highest total porosity among the experimental sites. Moreover, the intense reworking of the soil during the embankment construction reduced its compaction. However, despite the high total volume of voids, this particular particle arrangement drastically reduces the size of the interconnected channels through which water can flow. This limits water transfer to deeper zones and, as a result, decreases water mobility, thus leading to lower soil permeability (Figure 6.2). Sites 846 and 915 exhibited a significantly lower water storage capacity compared to Site 850, while maintaining a mutual similarity. These experimental sites resulted in a very high hydraulic conductivity, which remained consistently high even at elevated suctions. This characteristic promoted efficient drainage and uniform soil dehydration, thereby preventing the formation of permanent water deposits which could, in the long term, induce the generation of positive pore-water pressures within the soil mass. Table 6.1 highlights the main hydrological differences between the analysed sites in terms of storage capacity and permeability at both high and low suction values.

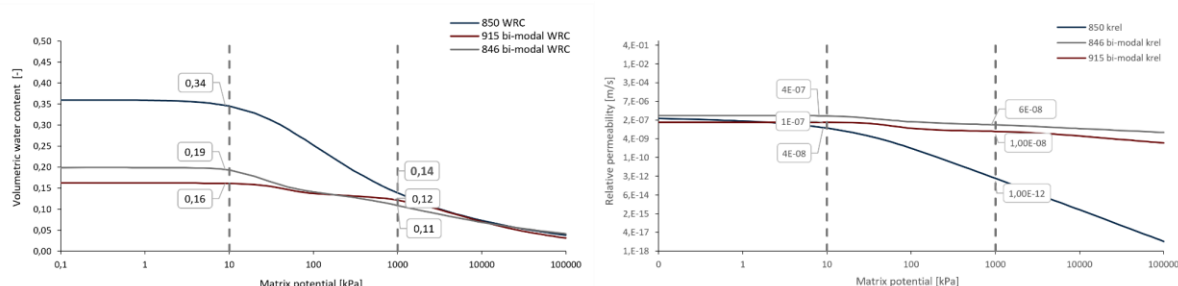


Figure 6.2 - Comparison of water retention curves (WRC) and relative permeability curves (k_{rel}) for each experimental site, with an emphasis on low ($\psi=10$ kPa) and high suction ($\psi=1000$ kPa) conditions.

Table 6.1 - Comparison of the hydraulic characteristics of the three experimental sites.

INTRINSIC HYDROLOGICAL PROPERTIES			
	Storage capacity	$K_{rel_}\Psi = 10$	$K_{rel_}\Psi = 1000$
SITE 846	Low	High_1E-7	High_1E-8
SITE 915	Low	High_4E-7	High_6E-8
SITE 850	High	High_4E-8	Low_1E-12

Numerical models developed using monitoring data were validated with the SEEP/W module of the GeoStudio software package. This flow analysis proved essential for model validation and for defining the two-dimensional variation of pore pressures across the entire soil profile, thereby extending the analysis beyond the single measuring points.

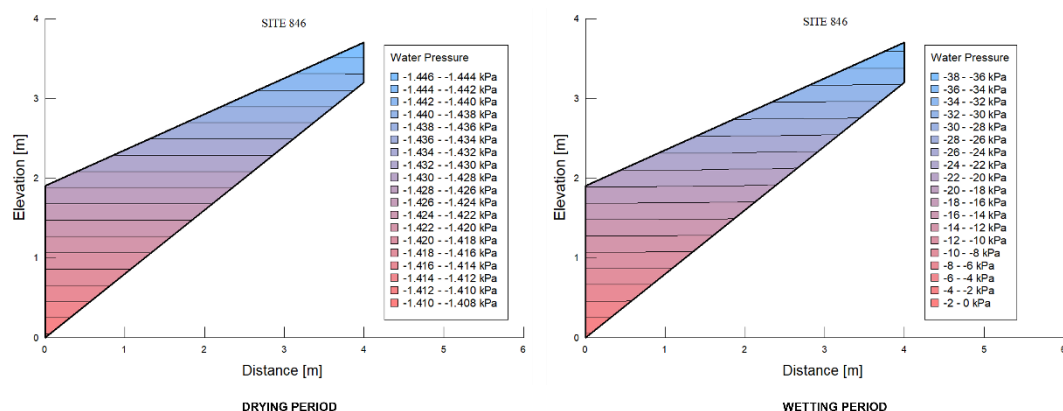


Figure 6.3 - Pore pressure distribution during the drying and wetting periods at Site 846.

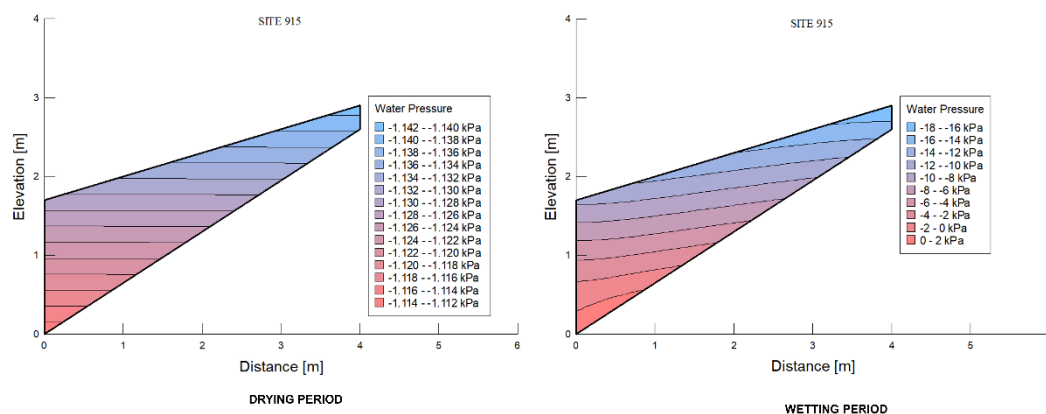


Figure 6.4 - Pore pressure distribution during the drying and wetting periods at Site 915.

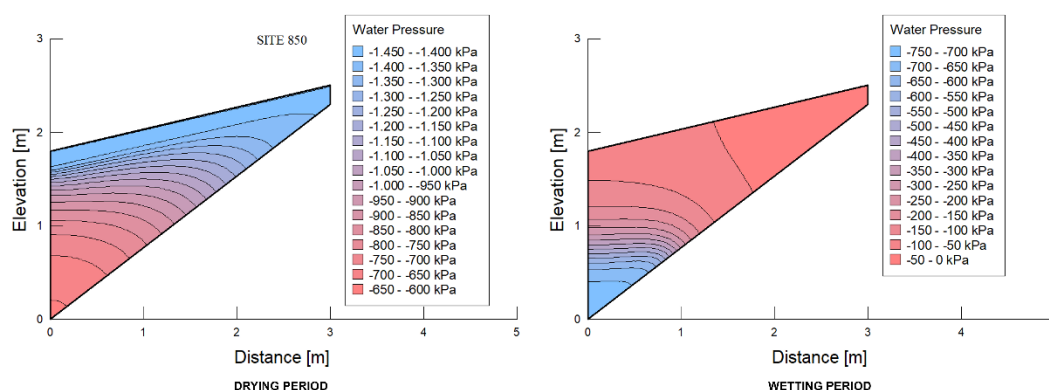


Figure 6.5 - Pore pressure distribution during the drying and wetting periods at Site 850.

The results of the flow analysis confirmed the simulations of the hydrological model, highlighting a distinct differentiation in hydrological behaviour among the experimental sites. Specifically, sites 846 and 915 exhibited a homogeneous pore pressure distribution throughout the profile, in both the drying and wetting phases (Figure 6.3 and 6.5). This homogeneity is directly correlated with the uniform distribution of roots at depth, which ensures a more effective and consistent regulation of the suction value, modulated by evapotranspiration and the vegetation type.

Conversely, Site 850 exhibited a tendency to significantly modulate the soil's saturation state, being almost exclusively confined to the shallow layer during both hydrological phases (Figure 6.5). This phenomenon may have led to a non-uniform distribution of effective stresses, consequently generating a heterogeneous pore-water pressure gradient along the slope profile. Moreover, at Site 850, a significantly more pronounced soil saturation/desaturation cycle, especially confined to the surface, was found. This means that the abrupt change in moisture content is localised, creating a heterogeneous distribution of effective stresses. Consequently, this generates a pore-water pressure gradient that varies with depth along the slope. The differential distribution of pore water pressure can result from the combination of two factors: the soil's intrinsic hydrological behaviour and the predominant influence of vegetation, which likely acts almost exclusively on the shallow layer.

Based on the simulated hydrological dynamics, a limit equilibrium stability analysis was performed for each site, which allowed for the evaluation of the variation in the Factor of Safety (SF) as a function of different pore pressures and for each time interval of the hydrological cycle. The results highlighted that the Factor of Safety showed a variable trend within the same experimental sites in relation to the alternation of drying and wetting phases.

Following these results, an investigation on the factors that influence the sites stability during the drying and wetting phases was conducted. The findings from this comparison (see paragraph 5.4) showed that, during the drying phase (where the evapotranspiration process is dominant), the type of vegetation significantly affects the evapotranspiration rates and, consequently, the suction value.

Observing figure 6.6, Site 850 resulted in the most critical scenario during the drying phase, given the combination of a high-water content, a significantly reduced suction, and a root distribution limited to the surface layer. These characteristics concurred most to reduce resisting forces. Regarding the parameters that influenced the driving forces, the lower slope gradient may be the most significant.

Therefore, it can be stated that despite Site 850 resulted in intrinsically more stable conditions concerning the factors influencing driving forces (i.e., weight and slope inclination), its relative stability during the drying phase can be reduced. This may depend on the type of vegetative cover, whose action is here restricted to the shallowest layer. This evidence highlights that, in the absence of a deep root system, the influence of vegetation on evapotranspiration rates and, consequently, on matric suction assumes a dominant and primary role. This hydrological impact seem thus may be more important than the contribution of both the mechanical and geometric parameters (e.g., slope angle and profile thickness). Conversely, at Sites 915 and 846, where the parameters controlling resisting forces are highly similar, the influence of the geometric parameters on the Factor of Safety is considerably greater (Figures 6.6 and 6.8).

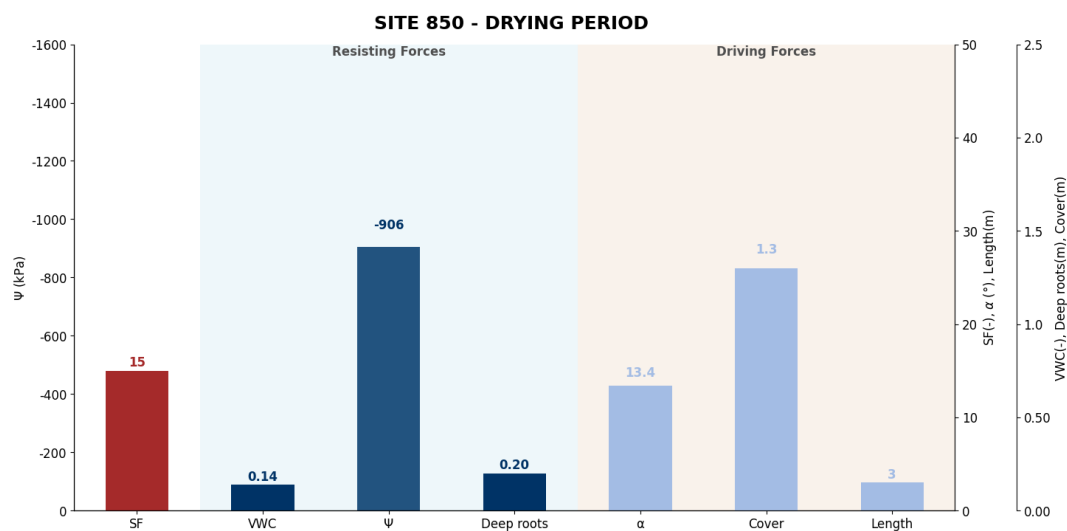


Figure 6.6 – Summary of the variables influencing slope stability at site 850 during the drying period (the variables are separated into driving and resisting forces).

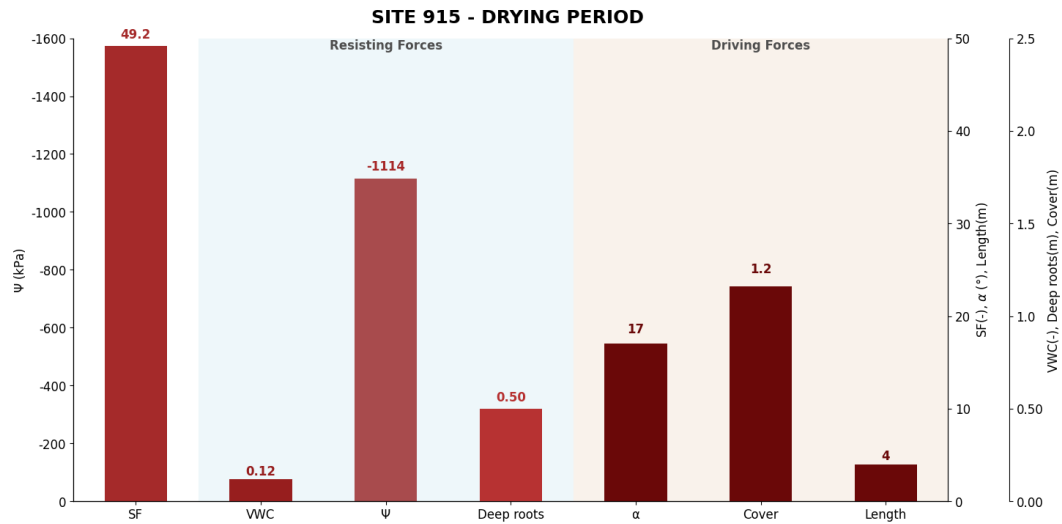


Figure 6.7 – Summary of the variables influencing slope stability at site 915 during the drying period (the variables are separated into driving and resisting forces).

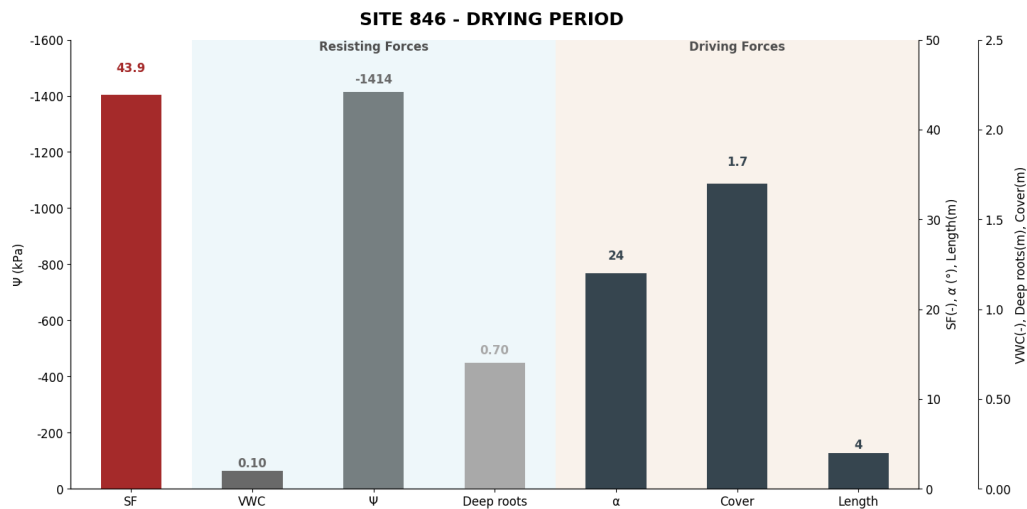


Figure 6.8 – Summary of the variables influencing slope stability at site 846 during the drying period (the variables are separated into driving and resisting forces).

The analysis of these results suggests that, during the drying phase, the contribution of vegetation acts as a determining factor for the stability of terraces. Specifically, the input of suction induced by the vegetation cover play a crucial role in effectively counteracting instability phenomena.

During the wetting phase, a substantial reversal in soil stability conditions was observed. The reduced or sometimes absent role of evapotranspiration, primarily due to the greater influence of precipitation and infiltration processes, affected the stabilizing contribution of suction. Given that infiltration represents the prevalent hydrological process in this phase, the stability

was found to exhibit a major sensitivity to both the terrace's geometry and the soil's hydraulic conductivity. By analysing the factors influencing the stability of the examined sites, it was found that the Factor of Safety (SF) was lower for sites 846 and 915 during this phase. The role of vegetation was marginally relevant in the wetting phase, given the limited evapotranspiration process and the resulting minimal suction contribution the vegetation imparts to the soil (Figures 6.9 and 6.11). However, at Site 850 a significantly elevated suction was still found (Figure 6.9). This value may be attributable to the soil intrinsic hydrological characteristics, particularly its low permeability at high suction levels, which may slow down the infiltration process into the soil, allowing the elevated suction values generated during the previous drying phase to be maintained. At sites 915 and 846, the contribution of suction in terms of stabilising forces was found to be significantly reduced compared to the drying phase. Therefore, in this scenario, the geometric factors of the slope become relevant. Notably, although Site 846 presents a more critical geometric condition than Site 915, it exhibited a higher Factor of Safety (Figure 6.10 and 6.11). This may be explained because Site 846 shows a greater resisting force, determined by suction, compared to Site 915. Therefore, it may be assumed that the higher suction value at Site 846 is the effect of a higher drainage capacity, promoted by the joint combination of slightly higher permeability, greater soil thickness, and a greater slope gradient, factors that favour drainage. Conversely, at Site 915, where soil cover thickness and slope gradient are lower, the drainage efficiency may be less effective, thus promoting water accumulation, which negatively influences the soil suction.

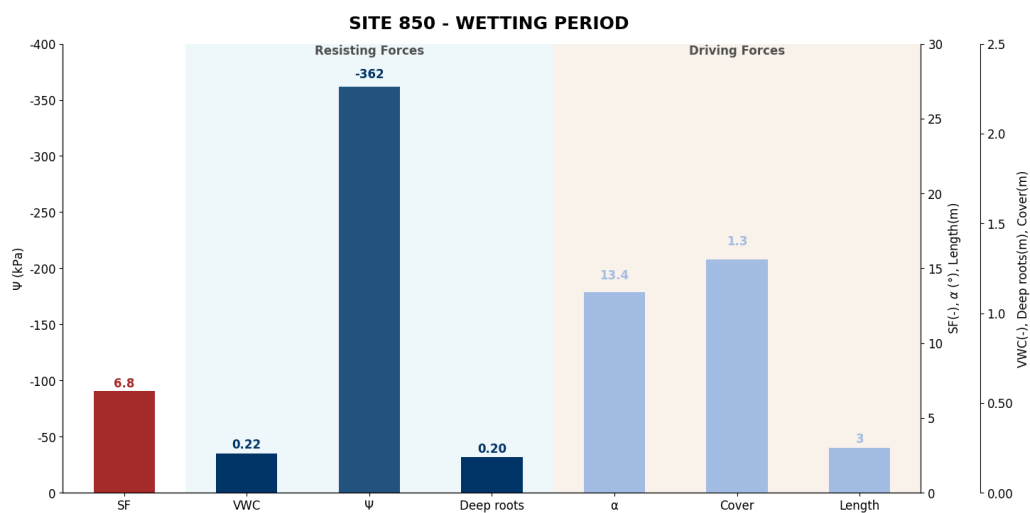


Figure 6.9 – Summary of the variables influencing slope stability at site 850 during the wetting period (the variables are separated into driving and resisting forces).

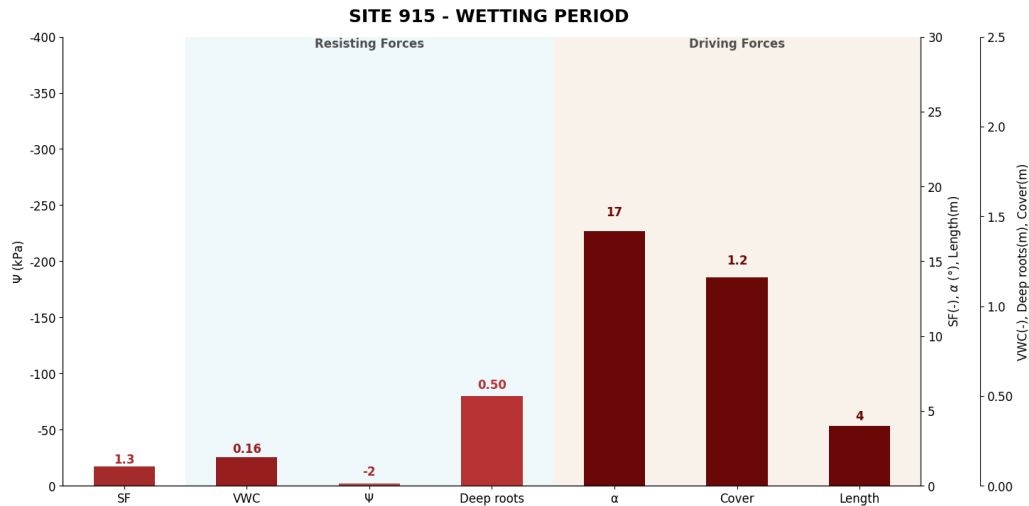


Figure 6.10 – Summary of the variables influencing slope stability at site 915 during the wetting period (the variables are separated into driving and resisting forces).

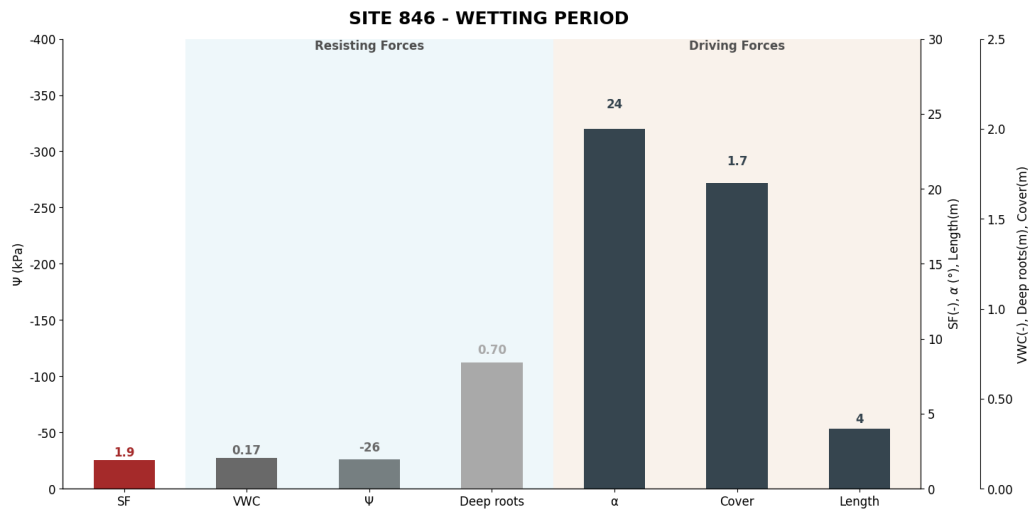


Figure 6.11 – Summary of the variables influencing slope stability at site 846 during the wetting period (the variables are separated into driving and resisting forces).

Figure 6.12 provides a comprehensive conceptual scheme of the critical observations derived from the detailed-scale analysis of the terrace-dry-stone-wall system.

This conceptual scheme was structured to establish a direct correlation between the stability analysis results and the variation in the system's hydrological phases.

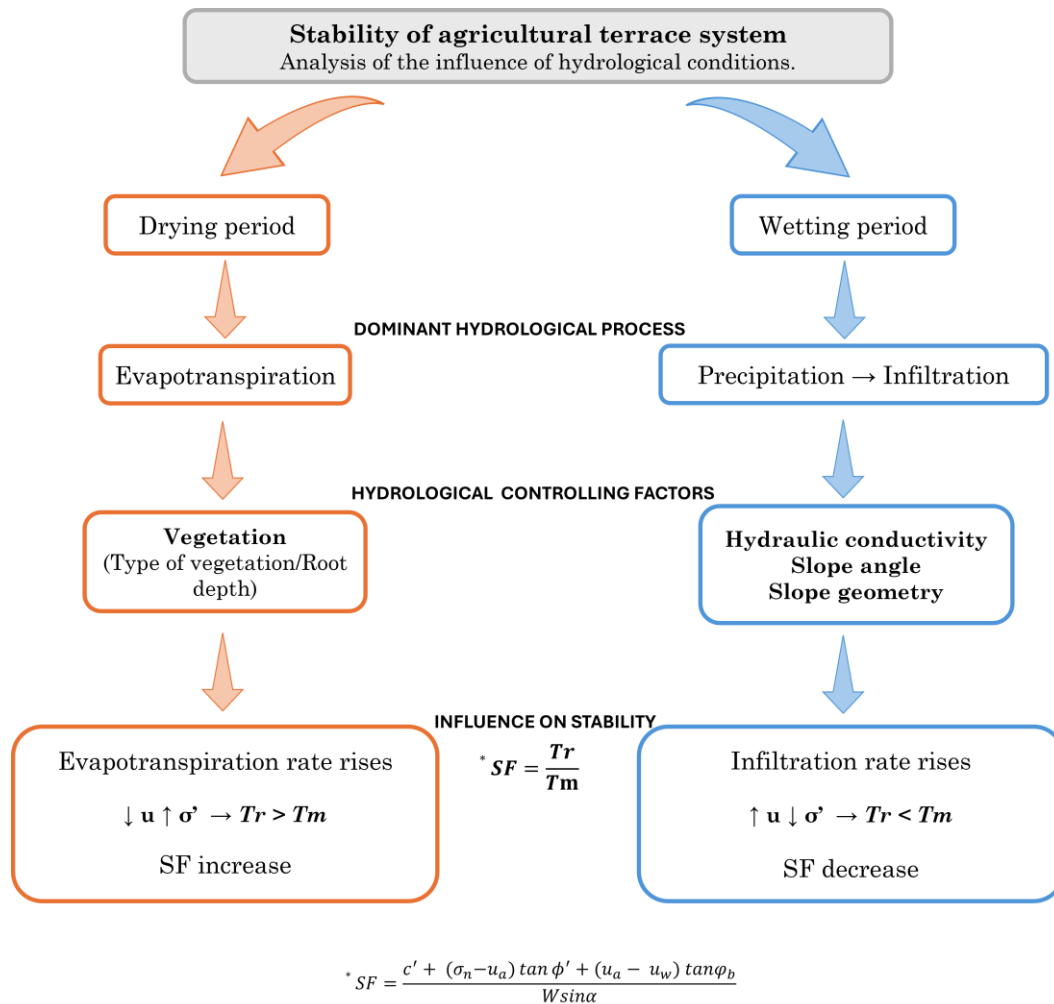


Figure 6.12 - Conceptual scheme summarizing the results of the limit equilibrium stability analysis.

The coupled flow-deformation analysis, performed using PLAXIS software, allowed for the validation of the hydro-mechanical model of Site 850. This preliminary stage was crucial for the subsequent assessment analysis of the operational condition this site, specifically to analyse the variation of total horizontal stresses in the soil-structure interaction as a function of changing hydrological cycle (drying-wetting phases).

Although the validation was predominantly qualitative, the results obtained proved to be consistent in terms of trend with those measured in situ. In particular, the variation in the simulated stresses was coherent with the seasonal variations observed in the field.

The observed discrepancy in the temporal data sets (numerical model and in situ measurements) was a time lag, a phenomenon extensively discussed in Paragraph 5.5.5.

It was hypothesised that this delay could be attributable to issues stemming from the installation procedures, specifically defects in adhesion or interference phenomena between the pressure cell, the adhesive mortar employed, and the surrounding ground. Given that the results of the

initial analysis highlighted the influence of various factors on the local stability of the terracing-dry-stone wall system, a subsequent analysis became necessary to isolate the action of vegetation. To this end, the intrinsic geometry and hydrological conditions of the validated model for Site 850 were kept constant. The introduced variable was the evapotranspiration rate, as it is representative of different vegetative conditions. The specific objective of this analysis was to study the variation of total horizontal pressures at the soil-structure interface as a function of different land-use conditions.

Based on the validation results, the influence of different land use on the development of lateral pressures at the soil-structure interface was then evaluated (Figure 6.13). Extreme vegetative conditions were considered: total absence of vegetation and the presence of cultivated vegetation (Model B), representing the optimal condition. These conditions were compared with the vegetation conditions present at Site 850 (Model A) to assess their influence on the development of horizontal stresses with varying hydrological conditions (drying and wetting). In the initial drying phases (Phases 1-3), both Model A and Model B operate within a suction-dominated regime, exhibiting positive and near-equivalent horizontal stresses. A marked divergence is observed between Phase 4 and the peak drying condition (Phase 7): Model B achieved significantly higher positive suction values, whereas Model A showed a less substantial increase. Crucially, both models maintained a suction regime, thus exerting no pressure on the structure. Upon the onset of the wetting period (from Phase 8), the positive stresses diminished. At the peak wetting phase, Model A underwent a regime inversion: the total horizontal stresses at the base become negative (reaching approximately -25 kPa), signifying a transition towards the saturated condition and the consequent onset of pressure acting on the wall. Conversely, Model B consistently maintains its suction-dominated regime, thereby ensuring the absence of active pressure on the structure. Consequently, it was inferred that the presence of cultivated vegetation (Model B) imparts greater stability to the slope-wall system compared to conditions of vegetative absence or abandonment (Model A at peak wetting). The persistence of Model B in the suction regime, even during critical hydrological conditions, proved decisive for maintaining the structural integrity of the retaining wall.

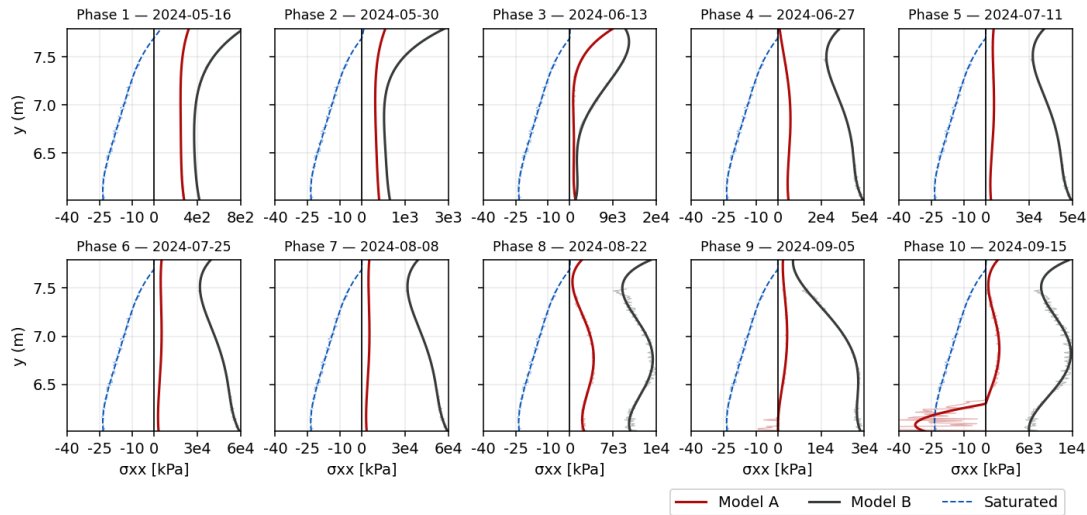


Figure 6.13 - Variation of the horizontal stress exerted by the soil on the wall, considering three different land use conditions.

Assuming similar geometry and intrinsic hydrological properties, data demonstrated that the presence of cultivated vegetation on the soil confers greater stability, particularly during the drying phase. Although both land-use conditions proved stable during this phase under the meteorological conditions analysed, the most salient finding emerges in the wetting phase. This latter phase, which represents the critical hydrological condition for risk assessment, showed that the cultivated site (Model B) benefits from markedly superior stability compared to the site with spontaneous, shallow vegetation (Model A).

These conclusions support the extensive evidence reported in the literature from basin-scale studies (Cevasco et al., 2014; Brandolini et al., 2018; Raso et al., 2018; Schilirò et al., 2018; Agnoletti et al., 2019; Moreno-de-las-Heras et al., 2019; Pepe et al., 2019; Di Napoli et al., 2020; Raimondi et al., 2023), which found a greater frequency of landslide occurrence on recently abandoned terraces compared to those maintained under cultivation or those abandoned for long time and covered from dense vegetation. Interestingly, this study allowed to accurately investigate and quantify the mechanism by which different land-use conditions can influence stability at the scale of the single terraced system.

A good agreement was found when comparing the data from the local analysis with the results obtained from the slope stability analysis, particularly regarding the drying phase. In both studies, the crucial influence of the soil's vegetative condition on site stability is confirmed.

This finding is significant as it outlines the importance of the evapotranspiration process. During the drying phase, in the presence of cultivated or long-term abandoned (“dense cover”)

vegetation, evapotranspiration promotes an increase in soil suction, which in turn enhances the mechanical resistance of the soil.

The situation is reversed, however, showing a significant discrepancy during the wetting phase. In the results of the previous stability analysis, Site 850 (Model A) was found to be more stable than the cultivated Site 915 (Model B). This stands in direct contrast to the findings from the coupled analysis conducted in PLAXIS. The reason for this discrepancy lies in the differing methodological approaches. The initial stability analysis gave weight to the site's intrinsic geometries and the soil's native hydrological conditions. Conversely, in the coupled analysis, these factors were intentionally disregarded. The purpose of this second case was precisely to isolate and investigate the role of vegetation on site stability, thus eliminating the influence of other geotechnical and hydrological variables.

Therefore, this study has allowed for the quantification of reliable hydrological models for three different land-use scenarios. This was achieved through the analysis of monitoring data, and the resulting models were comprehensively validated using numerical modelling. Flow, stability, and stress-strain analyses enabled the quantitative investigation of the factors influencing stability, particularly the role of vegetation. These analyses revealed that the dynamics affecting the local stability of the terraced dry-stone wall system correlate primarily with the type of vegetation. A slope that is either cultivated or has well-developed shrub vegetation confers good stability, even on slopes characterized by greater slope gradient and cover thickness. Further elements that should require investigation in future studies can be related to the intrinsic hydrological properties of the soil, which in some cases are closely linked to vegetation due to conditions that increase organic matter production and influence water storage capacity, as well as the geometric characteristics of the terraced dry-stone wall system itself. In reference to slope-scale stability, the results of this study indicate that one of the main causal factors of global instability, thus involving large area and/or large volumes of material, is correlated with the mechanical properties of the bedrock or the soil on which the dry-stone wall foundation is settled.

CONCLUSIONS

The Cinque Terre region is facing increasing geo-hydrological instability across its terraced landscape. This critical issue is being exacerbated by the synergistic effect of two crucial factors: alterations in rainfall patterns, attributable to climate change, and the progressive abandonment of agricultural terraced slopes. This has led to widespread slope degradation involving both erosional and mass movement processes, ranging from large-scale phenomena involving entire hillsides to localised collapses affecting individual dry-stone wall-terrace systems. This slope evolution has produced significant socio-economic losses and critically threatens the integrity of the cultural heritage within the Cinque Terre National Park. The UNESCO World Heritage recognition attests to the exceptional value of this cultural landscape, necessitating its urgent protection. Consequently, the preservation of these terraced systems is not merely a local concern but assumes global significance.

To effectively counteract the phenomenon of geomorphological instability and preserve the cultural landscape of the Cinque Terre, it is essential to precisely identify the driving factors influencing its development. The current state-of-the-art concerning terraced slopes reveals a significant gap in studies that comprehensively integrate hydrological, geotechnical, and climatic monitoring for the quantitative analysis of the factors influencing the stability of terraced systems at the local scale. Furthermore, a lack of research is noted regarding how the influence of these factors may vary according to the different phases of the hydrological cycle. Specifically, there is a shortage in investigating the hydrological dynamics that develop on the slopes in response to variable water regimes, as well as in the quantification of the vegetation's contribution to the stability analysis.

The primary objective is to acquire an in-depth understanding of the characteristics of the terraced slopes that are most important in producing instability scenarios. Indeed, their comprehension is fundamental for the elaboration of effective mitigation strategies aimed at preventing or mitigating slope degradation. To this end, the present study sought to thoroughly investigate some of these factors by using a multi-scale methodological approach, involving analyses at both the slope and the local scale.

The results obtained from the slope-scale analysis clearly demonstrated that one of the most significant factors in determining stability is the structure of the slope itself and, in particular, the construction characteristics of the dry-stone wall foundation. Indeed, stability was found strongly conditioned by both the setting depth of the wall relative to the soil cover and by the mechanical properties of the foundation material. These structural aspects were found to be key

indicators defining the dimensions and magnitude of a potential landslide event at the slope scale.

Furthermore, the analysis revealed that areas where dry-stone walls are directly founded on the bedrock, instability phenomena tend to be localised at individual dry-stone wall terraces. This evidence moved the analysis at the scale of the single terrace, directing the research toward a detailed analysis focused on the factors influencing its stability. To this end, and to ensure a comprehensive and representative overview of the triggering mechanisms, three distinct experimental terraced systems were selected and analysed in detail. These sites were chosen by virtue of their differentiated geomorphological and vegetative setting, thereby making it possible to capture the full spectrum of factors that can influence the triggering of instability at the single terrace scale.

Hydrological models of the terrace were constructed based on the quantitative interpretation of data acquired through hydrological and mechanical monitoring. These models were subsequently validated via the implementation of numerical models, which were employed to simulate flow analyses, limit equilibrium stability analyses, and fully coupled flow-deformation analyses.

The most innovative element of this analytical methodology lies in the quantification of the vegetation's contribution. Unlike prevailing approaches in the literature, where the stabilising effect is typically expressed through root reinforcement analysis (aimed at determining a value for the apparent root cohesion), in this study the cohesive contribution of vegetation to the soil was calculated indirectly. This was achieved by quantifying the matric suction generated by the evapotranspiration process, thereby incorporating the hydro-mechanical contribution instead of the purely mechanical one. Under these circumstances, the evapotranspiration rate, which depends on the type of vegetation and specific vegetative conditions, was calculated using the Penman-Monteith formula.

By examining the terrace site behaviour in relation to the two fundamental phases of the hydrological cycle (i.e., dry and wet), it emerged that vegetation plays a crucial stabilising role only under specific conditions: namely, in the presence of cultivated vegetation or in a situation of prolonged abandonment that has favoured the development of spontaneous plants with well-established root systems in the soil. Conversely, the vegetative condition following recent abandonment, characterised by the prevalence of only superficial spontaneous grass, was found to be the scenario most prone to instability. This crucial observation emphasizes that the effectiveness of the stabilising contribution does not strictly depend on the presence of vegetation, but rather on both its type and degree of root development. These characteristics are

fundamental as they determine the capacity of the vegetation cover to induce suction in the soil through the process of evapotranspiration, thereby modulating the hydrological regime and, consequently, the soil mechanical resistance.

Anyway, it is relevant to note that this is strictly valid in the context of slopes characterized by similar and homogeneous geometric, geomorphological, geological, and hydrological characteristics. However, when these parameters prove to be site-specific, the factors influencing stability may undergo a significant variation, particularly in relation to the different phases of the hydrological cycle.

During the drying phase, characterised by the dominance of evapotranspiration processes, the results confirmed that, despite different site conditions (i.e., geometric, geological, etc.), the stabilising role of vegetation remains primary. Consequently, sites that are in a state of recent abandonment are identified as being the most prone to instability. Conversely, in the wetting phase, where the infiltration of rainwater processes prevails over evapotranspiration, the contribution of mechanical reinforcement in the soil derived from vegetation-induced suction is significantly reduced. In this scenario, site-specific conditions acquire a prominent role: in particular, the parameters linked to the terrace geometry, the thickness of the soil cover, and the slope gradient, which mainly affect destabilising forces.

This study provides an innovative and significant contribution to the field, filling apparent gaps in the existing scientific literature concerning the stability of terraced slopes.

The originality of this research lies in having conducted analyses at both the slope scale and the individual terrace-wall system level, with the explicit objective of quantifying the factors conditioning stability, placing a particular focus on the role of vegetation. This was made possible by using rigorous and reliable numerical models, which were developed and validated based on an extensive collection of in-situ hydrological and mechanical monitoring data. These models were successfully employed in flow and stability analyses, enabling the precise identification of influential factors.

In particular, an aspect of significant novelty is the quantification of the influence of vegetation on the development of total horizontal pressures (i.e., the compressive regime) at the soil-wall interface through fully coupled flow-deformation analyses. The mathematical model developed herein allowed this issue to be addressed, with the crucial validation of stresses achieved using data obtained from in-field mechanical monitoring.

The other element of innovation is the modelling of the mechanical contribution of vegetation through suction induced by the evapotranspiration process, thereby providing a novel interpretation for evaluating the stabilising role of the vegetation cover.

Based on the results achieved, and with the aim of effectively mitigating the instability affecting terraced slopes, this study may provide a useful contribute to the identification and implementation of specific strategies.

The primary action should be a rigorous assessment of the construction integrity of dry-stone walls. In line with the objectives of the "Stone Wall for Life" project, it is recommended that wall reconstruction interventions adopt a foundation depth congruent with the depth of the bedrock. This requirement is of crucial importance, representing a significant factor influencing the extent and magnitude of any potential slope instability process. A second strategy should involve the prioritization of the restoration of short-term abandoned terraces. The results have demonstrated that conditions of recent abandonment, characterised by superficial vegetation, are the most unstable. Therefore, implementing cultivation or other forms of management that favour the development of deep root systems is essential to restore the stabilising role of the vegetation.

Future research developments will aim at extending and deepening the current investigation, focusing specifically on the interaction between slope hydrodynamics and the structural integrity of the retaining elements. The main objective will be to investigate in detail the various dry-stone wall drainage conditions that can be affected by the hydrological circulation developing within terraced slopes. In parallel, the direct consequence of these hydrological dynamics on the deformational structure of the wall itself will be analysed. This prospective analysis will also include the evaluation of effects induced by extreme climatic conditions. This approach will allow for the development of a more complete understanding of failure mechanisms within a context of increasing climatic variability, providing essential data for the planning of resilient structural interventions.

REFERENCES

- Abbate, E. (1969). Geologia delle Cinque Terre e dell'entroterra di Levante (Liguria orientale). *Memorie della Società Geologica Italiana*, 8, 923–1014.
- Agnoletti, M., Errico, A., Santoro, A., Dani, A., & Preti, F. (2019). Terraced landscapes and hydrogeological risk. Effects of land abandonment in Cinque Terre (Italy) during severe rainfall events. *Sustainability*, 11(1), 235.
- Allen, R.G., L.S.Pereira, D. Raes, and M. Smith. 1998. "Crop evapotranspiration: guidelines for computing crop water requirements." Irrigation and Drainage Paper No. 56, Food and Agriculture Organization of the United Nations, Rome, Italy.
- APAT (Agenzia per la Protezione dell'Ambiente e per i servizi Tecnici)., 2007. Gli indicatori del CLIMA in Italia nel 2006. (Stato dell'Ambiente 11/2007). Roma: APAT.
- Associazione Geotecnica Italiana (AGI). (1994). Raccomandazioni sulla programmazione ed esecuzione delle indagini geotecniche e sull'interpretazione dei risultati.
- Aspetti, G. (2006). La Sostanza Organica e la Desertificazione: Aspetti Sperimentali e Modellistici. ENEA editore.
- Bentley Systems International Limited. (2024). PLAXIS 2D 2024.3 Material Model Manual.
- Bentley Systems International Limited. (2025). PLAXIS 2D 2024.3 Reference Manual.
- Bernini et al. (2021). Preliminary scientific and technical report. LifeProject "Stonewallforlife" deliverable – 36 pp.
- Besio, M. (2004). Manuale per la costruzione dei muri a secco: Linee guida per la manutenzione dei terrazzamenti delle Cinque Terre. Progetto LIFE-PROSIT (LIFE 00 ENV/IT/000191 PROSIT), Dipartimento Polis, Università di Genova.
- Bordoni, M., Meisina, C., Vercesi, A., Bischetti, G. B., Chiaradia, E., Bassanelli, C., ... & Chersich, S. (2014). Grapevine root system strength in an area susceptible to shallow landslides for slope stability assessment. In *I International Symposium on Grapevine Roots 1136* (pp. 81-88).
- Bordoni, A. Vercesi, M. Maerker, V. Vivaldi, and C. Meisina (2021). Impact of Agricultural Management in Vineyards to Landslides Susceptibility in Italian Apennines. Book-Volume 2 Understanding and Reducing Landslide Disaster Risk.
- Bosellini, A. (2005). *Storia geologica d'Italia*. Zanichelli - ISBN 88-08-07527-3.
- Brancucci, G., Gherzi, A., & Ruggiero, M. E. (2000). Paesaggi liguri a terrazze: Riflessioni per una metodologia di studio. Alinea Editrice.
- Brandolini, P., & Cevasco, A. (2014). Geo-hydrological risk mitigation measures and land-management in a highly vulnerable small coastal catchment. In *Engineering Geology for Society and Territory-Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation* (pp. 759-762). Cham: Springer International Publishing.

Brandolini, P. (2017). The outstanding terraced landscape of the Cinque Terre coastal slopes (eastern Liguria). *Landscapes and landforms of Italy*, 235-244.

Brandolini, P., Cevasco, A., Capolongo, D., Pepe, G., Lovergine, F., & Del Monte, M. (2018). Response of terraced slopes to a very intense rainfall event and relationships with land abandonment: A case study from Cinque Terre (Italy). *Land Degradation & Development*, 29(3), 630-642.

Brutsaert, W. (1982). Evaporation into the atmosphere. Dordrecht: Kluwer Academic Publisher.

Burger C (1999) Comparative evaporation measurements above commercial forestry and sugarcane canopies in the KwaZulu-Natal Midlands. MSc Dissertation, University of Natal, Pietermaritzburg, South Africa.

Canny, M.J. 1977. Flow and transport in plants. *Ann. Rev. Fluid Mech.* 9: 275-296.

Camera, C. A., Apuani, T., & Masetti, M. (2014). Mechanisms of failure on terraced slopes: the Valtellina case (northern Italy). *Landslides*, 11, 43-54.

Camera, C., Apuani, T., & Masetti, M. (2015). Modeling the stability of terraced slopes: an approach from Valtellina (Northern Italy). *Environmental earth sciences*, 74(1), 855-868.

Carl, T., & Richter, M. (1989). Geocological and morphological processes on abandoned vine-terraces in the Cinque Terre (Liguria). *Geoökodynamic*, 10, 125-158.

Cevasco, A. (2007). I fenomeni di instabilità nell'evoluzione della costa alta delle Cinque Terre (Liguria Orientale). *Studi costieri*, 13, 93-109.

Cevasco, A., Brandolini B., Scopesi C. & Rellini I. (2013). Relationships between geo-hydrological processes induced by heavy rainfall and land-use: the case of 25 October 2011 in the Vernazza catchment (Cinque Terre, NW Italy). *Journal of Maps*, 9(2), 289-298.

Cevasco, A., Diodato, N., Revellino, P., Fiorillo, F., Grelle, G., & Guadagno, F. M. (2015). Storminess and geo-hydrological events affecting small coastal basins in a terraced Mediterranean environment. *Science of the Total Environment*, 532, 208-219.

Cevasco, A., Pepe, G., D'Amato Avanzi, G. & Giannecchini, R. (2017). Preliminary analysis of the November 10, 2014 rainstorm and related landslides in the lower Lavagna Valley (Eastern Liguria). *Italian Journal of Engineering Geology and Environment*, 2017(Special Issue 1), 5-15. DOI: 10.4408/IJEGE.2017-01.S-01.

Chirico, G. B., Borga, M., Tarolli, P., Rigon, R., & Preti, F. (2013). Role of vegetation on slope stability under transient unsaturated conditions. *Procedia Environmental Sciences*, 19, 932-941.

Chok, Y. H., Jaksa, M. B., Kaggwa, W. S., & Griffiths, D. V. (2015). Assessing the influence of root reinforcement on slope stability by finite elements. *International Journal of Geo-Engineering*, 6, 1-13.

Climate Data, (2021). Climate Cinque Terre: Temperature, climate graph, Climate table for Cinque Terre [WWW Document]. URL <<https://en.climate-data.org/europe/italy/cinque-terre-10082/>>(accessed 5.7.21).

Crosta, G. B., Dal Negro, P., & Frattini, P. (2003). Soil slips and debris flows on terraced slopes. *Natural Hazards and Earth System Sciences*, 3(1/2), 31-42.

Cubrinovski, M., & Ishihara, K. (1999). Empirical correlation between SPT N-value and relative density for sandy soils. *Soils and Foundations*, 39(5), 61-71.

Corey, A. T. (1979), *Mechanics of Heterogeneous Fluids in Porous Media* (Reprinted 2003), Water Resour. Publ., Littleton, Colo.

D'Amato Avanzi, G., Galanti, Y., Giannecchini, R., Lo Presti, D., & Puccinelli, A. (2013). Estimation of soil properties of shallow landslide source areas by dynamic penetration tests: first outcomes from Northern Tuscany (Italy). *Bulletin of Engineering Geology and the Environment*, 72(3), 609-624.

Dastgerdi, A. S., Sargolini, M., Allred, S. B., Chatrchyan, A. M., Drescher, M., & DeGeer, C. (2022). Climate change risk reduction in cultural landscapes: Insights from Cinque Terre and Waterloo. *Land use policy*, 123, 106359.

De Mello, V. F. B. (1971). The Standard Penetration Test. *Proceedings of the 4th Panamerican Conference on Soil Mechanics and Foundation Engineering*, 1, 1–86.

Díaz, A. R., Sanleandro, P. M., Soriano, A. S., Serrato, F. B., & Faulkner, H. (2007). The causes of piping in a set of abandoned agricultural terraces in southeast Spain. *Catena*, 69(3), 282-293.

Di Napoli, M., Bausilio, G., Cevasco, A., Confuorto, P., Mandarino, A., & Calcaterra, D. (2020). Landslide susceptibility assessment by ensemble-based machine learning models. In *Workshop on World Landslide Forum* (pp. 225-231). Cham: Springer International Publishing.

Di Napoli, M., Di Martire, D., Bausilio, G., Calcaterra, D., Confuorto, P., Firpo, M., ... & Cevasco, A. (2021). Rainfall-induced shallow landslide detachment, transit and runout susceptibility mapping by integrating machine learning techniques and GIS-based approaches. *Water*, 13(4), 488.

Dumont, M., Taibi, S., Fleureau, J.-M., Abou Bekr, N., & Saouab, A. (2010). Modelling the effect of temperature on unsaturated soil behaviour. *Comptes Rendus Geoscience*, 342(10), 892–900.* <https://doi.org/10.1016/j.crte.2010.09.006>.

Durner, W. (1994). Hydraulic conductivity estimation for soils with heterogeneous pore structure. *Water Resources Research*, 30, 211–223.

Elter, P. (1994). Introduzione alla geologia dell'Appennino ligure-emiliano. *Guide geologiche regionali: Appennino ligure-emiliano*, BE-MA Ed, 17-24.

Epis, T. (2010). Valutazione del rinforzo radicale del suolo operato dalle radici delle principali specie forestali della Lombardia.

Facciorusso J., Madiati C., Vannucchi G. – DISPENSE DI GEOTECNICA, Dipartimento di Ingegneria Civile – Sezione Geotecnica, Università degli Studi di Firenze, 2006 e relativo materiale le lezioni.

Feddes, R. A. (1978). 4.3 Simulation of field water use and crop yield. Wageningen, the Netherlands: Centre for Agricultural Publishing and Documentation.

Fiorucci, M., Pepe, G., Marmoni, G. M., Pecci, M., Di Martire, D., Guerriero, L., ... & Scarascia Mugnozza, G. (2023). Long-term hydrological monitoring of soils in the terraced environment of Cinque Terre (north-western Italy). *Frontiers in Earth Science*, 11, 1285669.

Galavi, V., Brinkgreve, R.B.J., Bonnier, P.G., & Gonzalez, N.A. (2009). Fully coupled hydro-mechanical analysis of unsaturated soils. In Proceedings of the 1st International Symposium on Computational Geomechanics (COMGEO I). International Centre for Computational Engineering (IC²E).

Galeazzi, S., Ciabatta, L., Ciabatta, L., Salciarini, D., & Salciarini, D. (2024). a Model for Regional Slope Stability Analysis Incorporating Root Reinforcement Effects. In *Geological Society of America Abstracts* (Vol. 56, p. 402412).

GEO-SLOPE International Ltd. (2002) SEEP/W—per l'analisi delle infiltrazioni agli elementi finiti. Guida per l'utente, versione 5, Calgary.

Ghanbarian, B. (2021). Unsaturated hydraulic conductivity in dual-porosity soils: Percolation theory. *Soil and Tillage Research*, 212, 105061.

Gibbs, H. J., and Holtz, W. G. (1957). Research on determining the density of sands by spoon penetration testing, in 4th ICOSOMEF, London, 35–39.

Guarracino, L. (2007). Estimation of saturated hydraulic conductivity K_s from the van Genuchten shape parameter α . *Water resources research*, 43(11).

Gumbel, E. J. Statistics of Extremes. Columbia University Press, 1958.

Hales T. C., Ford C. R., Hwang T., Vose J. M., Band L. E., (2009). Topographic and ecologic controls on root reinforcement. *Journal of Geophysical Research*, VOL. 114, F03013, doi:10.1029/2008JF001168.

Harden, C. P. (1996). Interrelationships between land abandonment and land degradation: a case from the Ecuadorian Andes. *Mountain Research and Development*, 274-280.

Horton, R.E. (1939). “The interpretation and application of runoff plot experiments with reference to soil erosion problems”. *Soil Science Society of America Journal* 3 (C): 340-349.

Huat, B. B. K., Ali, F. H., & Choong, F. (2005). Volume change behavior of unsaturated residual soil. *Electronic Journal of Geotechnical Engineering*, 10(Bundle B).

- Kozeny, J. (1927). Ueber kapillare Leitung des Wassers im Boden. *Sitzungsberichte Wiener Akademie*, 136(2a): 271–30.
- Laganière, J., Augusto, L., Hatten, J. A., & Spielvogel, S. (2022). Vegetation effects on soil organic matter in forested ecosystems. *Frontiers in Forests and Global Change*, 4, 828701.
- Lesschen, J. P., Cammeraat, L. H., & Nieman, T. (2008). Erosion and terrace failure due to agricultural land abandonment in a semi-arid environment. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, 33(10), 1574-1584.
- Llorens, P., Latron, J., & Gallart, F. (1992). Analysis of the role of agricultural abandoned terraces on the hydrology and sediment dynamics in a small mountainous basin (High Llobregat, Eastern Pyrenees). *Pirineos*, 139, 27-46.
- Mao, Z. (2022). Root reinforcement models: Classification, criticism and perspectives. *Plant and soil*, 472(1), 17-28.
- Masi, E. B., Tofani, V., Rossi, G., Cuomo, S., Wu, W., Salciarini, D., & Catani, F. (2023). Effects of roots cohesion on regional distributed slope stability modelling. *Catena*, 222, 106853.
- METER Group, (2021). Teros 11 Manual. <https://metergroup.com/products/teros-11/>.
- METER Group (2021). Teros 21 Manual. <https://www.metergroup.com/en/meter-environment/products/teros-21/teros-21-tech-specs>.
- METER Group (2021c). Atmos 41 Manual. <https://www.metergroup.com/en/meter-environment/products/atmos-41/atmos-41-tech-specs>.
- Ministero delle Infrastrutture e dei Trasporti (2019). Circolare n. 7/2019 del Consiglio Superiore dei Lavori Pubblici: Istruzioni per l'applicazione delle "Nuove norme tecniche per le costruzioni" di cui al D.M. 17 gennaio 2018. Pubblicata in Gazzetta Ufficiale della Repubblica Italiana, Serie generale - n. 35, Supplemento ordinario n. 5, del 11/02/2019.
- Mikola R.G., (2017). ADONIS: A free finite element analysis software with an interactive graphical user interface for geoengineers. *Geo Ottawa*, 1-7.
- Mishra, S., & Parker, J. C. (1990). On the relation between saturated conductivity and capillary retention characteristics. *Groundwater*, 28(5), 775-777.
- Montheith, J.L., (1965) Evaporation and environment. The State and Movement of Water in Living Organisms, Proc. 19th Symp. Soc. Exp. Biol.: 205-233. Cambridge University Press.
- Moreno-de-las-Heras, M., Lindenberger, F., Latron, J., Lana-Renault, N., Llorens, P., Arnáez, J., ... & Gallart, F. (2019). Hydro-geomorphological consequences of the abandonment of agricultural terraces in the Mediterranean region: Key controlling factors and landscape stability patterns. *Geomorphology*, 333, 73-91.
- Morgenstern, N. R., & Price, V. E. (1965). The analysis of the stability of general slip surfaces. *Géotechnique*, 15(1), 79-93.

- Murgia, I., Giadrossich, F., Mao, Z., Cohen, D., Capra, G. F., & Schwarz, M. (2022). Modeling shallow landslides and root reinforcement: A review. *Ecological Engineering*, 181, 106671.
- Odebrecht, E., Schnaid, F., Rocha, M. M., and Bernardes, G. P. (2005). Energy efficiency for standard penetration tests. *J. Geotech. Geoenviron. Eng.* 131 (10), 1252–1263. doi:10.1061/(asce)1090-0241(2005)131:10(1252).
- Pizzi Instruments S.r.l. *Manuale d'uso e Manutenzione Celle di Pressione* (2020). Bagno a Ripoli (FI), Italia: Pizzi Instruments S.r.l..
- Philip, J. R. (1957). The theory of infiltration: 1. The infiltration equation and its solution. *Soil science*, 83(5), 345-358.
- Philip, J.R. 1966. Plant water relations: some physical aspects. *Ann. Rev. Plant Physiol.* 17: 245-268.
- Pradhan, S., Toll, D. G., Rosser, N. J., & Brain, M. J. (2022). An investigation of the combined effect of rainfall and road cut on landsliding. *Engineering Geology*, 307, 106787. <https://doi.org/10.1016/j.enggeo.2022.106787>.
- Preti, F. (2006). Stabilità dei versanti vegetati. *Manuale di Ingegneria Naturalistica*, 3.
- Preti, F., Caruso, M., Dani, A., Trucchi, P., & Tarolli, P. (2014). Caratterizzazione geomorfologica, geotecnica e idraulica di un versante terrazzato con muretti a secco: rilievi di campo e strumentazione sperimentale terraced slope field surveys and experimental equipment. *quaderni di idronomia montana*, 285-297.
- Preti, F., Guastini, E., Penna, D., Dani, A., Cassiani, G., Boaga, J., ... & Tarolli, P. (2018a). Conceptualization of water flow pathways in agricultural terraced landscapes. *Land degradation & development*, 29(3), 651-662.
- Preti, F., Errico, A., Caruso, M., Dani, A., & Guastini, E. (2018b). Dry-stone wall terrace monitoring and modelling. *Land Degradation & Development*, 29(6), 1806-1818.
- Pufahl, D. E., Fredlund, D. G., & Rahardjo, H. (1983). Lateral earth pressures in expansive clay soils. *Canadian Geotechnical Journal*, 20(2), 228-241.
- Raimondi, L. (2020). Valutazione e mitigazione dei rischi geo-idrologici derivanti da eventi catastrofici nell'area del Parco Nazionale delle Cinque Terre [Tesi di dottorato].
- Raimondi, L., Pepe, G., Firpo, M., Calcaterra, D., & Cevasco, A. (2023). An open-source and QGIS-integrated physically based model for Spatial Prediction of Rainfall-Induced Shallow Landslides (SPRIn-SL). *Environmental Modelling & Software*, 160, 105587.
- Rankine, W. J. M.. (1857). On the Stability of Loose Earth. *Philosophical Transactions of the Royal Society of London*, 147(0), 9–27. doi:10.1098/rstl.1857.0003.
- Raso, E., Mandarino, A., Pepe, G., Di Martire, D., Cevasco, A., Calcaterra, D., & Firpo, M. (2019). Landslide inventory of the cinque terre national park, Italy. In *IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018-Volume 1: Slope Stability: Case*

Histories, Landslide Mapping, Emerging Technologies (pp. 201-205). Cham: Springer International Publishing.

Raso, E., Di Martire, D., Cevasco, A., Calcaterra, D., Scarpellini, P., & Firpo, M. (2020). Evaluation of prediction capability of the MaxEnt and Frequency Ratio methods for landslide susceptibility in the Vernazza catchment (Cinque Terre, Italy). *Applied geology: approaches to future resource management*, 299-316.

Raso, E., Mandarino, A., Pepe, G., Calcaterra, D., Cevasco, A., Confuorto, P., ... & Firpo, M. (2021). Geomorphology of cinque Terre national park (Italy). *Journal of Maps*, 17(3), 171-184.

Richards, L. A. (1931). Capillary conduction of liquids through porous mediums. *physics*, 1(5), 318-333.

Rotisciani, G.M., Desideri, A. & Amorosi, A. Unsaturated structured soils: constitutive modelling and stability analyses. *Acta Geotech.* 16, 3355–3380 (2021). <https://doi.org/10.1007/s11440-021-01313-7>.

Schilirò, L., Cevasco, A., Esposito, C., & Mugnozza, G. S. (2017). Role of land use in landslide initiation on terraced slopes: inferences from numerical modelling. In *Advancing Culture of Living with Landslides: Volume 4 Diversity of Landslide Forms* (pp. 315-320). Springer International Publishing.

Schilirò, L., Cevasco, A., Esposito, C., & Mugnozza, G. S. (2018). Shallow landslide initiation on terraced slopes: inferences from a physically based approach. *Geomatics, Natural Hazards and Risk*, 9(1), 295-324.

Seneviratne, S., Nicholls, N., Easterling, D., Goodess, C., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., & Zhang, X. (2012). Changes in climate extremes and their impacts on the natural physical environment. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC) (pp. 109–230). Cambridge University Press.

Šimanský, V., Jonczak, J., Pikuła, D., & Lukac, M. (2023). Grass sward cover improves soil organic carbon and nitrogen in a vineyard. *Soil Science and Plant Nutrition*, 69(4), 240-249.

Shioi, Y., & Fukuni, N. (1982). Application of N-value to design of foundations in Japan. In *Proceedings of the 2nd European Symposium on Penetration Testing* (Vol. 1, pp. 40-93).

Stanchi, S., Freppaz, M., Agnelli, A., Reinsch, T., & Zanini, E. (2012). Properties, best management practices and conservation of terraced soils in Southern Europe (from Mediterranean areas to the Alps): A review. *Quaternary International*, 265, 90-100.

Stasi, N., Tagarelli, V., Bottiglieri, O., & Cafaro, F. (2025). On the Use of a Water Potential Probe for Suction and Temperature Measurements in Unsaturated Natural Clayey Soil. *Applied Sciences*, 15(6), 3021.

- Stefanoff, G., Sanglerat, G., Bergdahl, U., and Melzer, K. J. (1988). Dynamic probing (DP): international reference test procedure. *Proceeding 1st Int. symposium penetration Test.* 1, 53–70.
- Taguas, E. V., Arroyo, C., Lora, A., Guzmán, G., Vanderlinden, K., & Gómez, J. A. (2015). Exploring the linkage between spontaneous grass cover biodiversity and soil degradation in two olive orchard microcatchments with contrasting environmental and management conditions. *Soil*, 1(2), 651-664.
- Tarantino, A., & Roberts-Self, E. (2023). Transpiration in the water-limited regime: soil-plant-atmosphere interactions. In *E3S Web of Conferences* (Vol. 382).
- Tarantino, A. (2010). Basic concepts in the mechanics and hydraulics of unsaturated geomaterials. <http://dx.doi.org/10.1002/9781118616871.ch1>.
- Tarantino, A. (2016). Technical criteria and procedures for designing vegetation effects (Deliverable No. D.2.3). RESCUE Project.
- Tarantino, A., & Di Donna, A. (2019). Mechanics of unsaturated soils: Simple approaches for routine engineering practice. *Italian Geotechnical Journal*, (4).
- Tarantino, A., & Roberts-Self, E. (2023). Transpiration in the water-limited regime: soil-plant-atmosphere interactions. In *E3S Web of Conferences* (Vol. 382).
- Tarolli, P., Rizzo, D., & Brancucci, G. (2019). Terraced landscapes: Land abandonment, soil degradation, and suitable management. In S. F. T. P. A. A. S. A. S. B. B. S. A. G. G. H. H. J. J. L. A. S. L. A. S. P. (Ed.), *World terraced landscapes: History, environment, quality of life* (pp. 195–210). Edizioni ETS.
- Terranova, R. (1989). Il paesaggio costiero agrario terrazzato delle Cinque Terre in Liguria. *Studi e Ricerche di Geografia*, 12(1), 1–58.
- Terranova, R., Brandolini, P., Spotorno, M., Rota, M., Montanari, C., Galassi, D., & Mus-Amezquita, M. (2002). Patrimoni de marjades a la Mediterrania Occidental. Una proposta de catalogació.
- Terranova, R., Zanzucchi, G., Bernini, M., Brandolini, P., Campobasso, S., Faccini, F., & Zanzucchi, F. (2006). Geologia, geomorfologia e vini del parco Nazionale delle Cinque Terre (Liguria, Italia). *Bollettino della Società Geologica Italiana Spec*, 6, 115-128.
- Trombetti F and Tagliazucca M (1994) Characteristic scales of atmospheric surface layer. Technical Paper No. 4, FISBAT-TP-94/1, Istituto FISBAT-C.N.R. Bologna, Italy.
- Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil science society of America journal*, 44(5), 892-898.
- Vannucci, S., D'Amato Avanzi, G., Galanti, Y., Giannecchini, R., Lo Presti, D., & Capilleri, P. (2019). Strength parameters of debris using a large shear box apparatus: application to a case history. *Rock Mechanics and Rock Engineering*, 52, 4421-4437.

Watt, C., Emelko, M. B., Silins, U., Collins, A. L., & Stone, M. (2021). Anthropogenic and climate-exacerbated landscape disturbances converge to alter phosphorus bioavailability in an oligotrophic river. *Water*, 13(22), 3151.

Wilson, G. W., Fredlund, D. G., & Barbour, S. L. (1997). The effect of soil suction on evaporative fluxes from soil surfaces. *Canadian Geotechnical Journal*, 34(1), 145-155.

Zhang, Y., Weihermüller, L., Toth, B., Noman, M., & Vereecken, H. (2022). Analyzing dual porosity in soil hydraulic properties using soil databases for pedotransfer function development. *Vadose Zone Journal*, 21(5), e20227.

Zhou, Y., Pei, Z., Su, J., Zhang, J., Zheng, Y., Ni, J., ... & Wang, R. (2012). Comparing soil organic carbon dynamics in perennial grasses and shrubs in a saline-alkaline arid region, northwestern China.

Zienkiewicz, O. C., Taylor, R. L., & Zhu, J. Z. (2005). The finite element method: Its basis and fundamentals (6th ed.). Elsevier Butterworth-Heinemann.

WEBLIOGRAPHY

<https://www.geostru.eu/blog/2018/06/21/stabilita-dei-pendii-2/>

http://www.idrologia.polito.it/didattica/Idrologia/2011/Argomento_7/IDF_corretto-1.pdf

https://moodle2.units.it/pluginfile.php/265658/mod_resource/content/1/Richiami%20%20-%20Spinta%20delle%20terre%20%28Rankine%29.pdf

https://help.geostru.eu/slope/it/metodo_di_mongester_e_price.htm

APPENDIX 1

Preliminarily within this chapter, it is essential to highlight that the site characterisation investigations, reported in paragraphs A.1 to A.2, were conducted entirely as part of the activities of the Stone wall for Life Project. As these investigations are based on standard and well-established procedures, the description of the methodologies adopted will be presented in a synthetic and concise manner.

A.1 SITE CHARACTERIZATION METHODS – IN SITU INVESTIGATIONS

To develop a representative engineering-geological model of the experimental sites, a comprehensive engineering-geological investigation program involving both in-situ and laboratory testing was conducted. The primary objective of the in-situ investigations was to characterise the subsurface conditions (e.g., soil thickness) using both direct and indirect methods.

Specifically, seismic refraction surveys to ascertain the depth and geometry of the bedrock and the thickness of the overlying soil layer horizons were performed. This geophysical technique, coupled with dynamic penetration tests, provided crucial information on the stratigraphic and mechanical properties within the soil profile. Moreover, this investigation approach enabled a more complete understanding of the subsurface geometry, which was essential for subsequent geotechnical modelling.

Other targeted in-situ tests to characterise the soil from both a mechanical and hydrological perspective were conducted: in-situ soil density tests (i.e., sand cone method), for determining the water content and unit weight of the soil in its natural conditions; double ring infiltrometer tests, which allowed for the assessment of soil water infiltration capacity and saturated permeability. The results obtained from the field tests have been of paramount importance for setting up and calibrating the subsequent hydrological and geomechanical models, ensuring that the models accurately reflect the real behaviour of the soil.

A.1.1 P-waves seismic refraction surveys

The refraction seismic test is a non-invasive geophysical technique that studies the propagation of seismic waves in the subsurface. This survey allows for the definition of a detailed stratigraphic model by indirectly identifying soil types and estimating the approximate depth of layer boundaries (e.g., soil-bedrock interface). Furthermore, when combined with other analyses, it helps defining the elastic parameters of materials.

The seismic refraction data were acquired along 4 alignments, three of which oriented roughly parallel to the local dip direction of the slope and whose traces pass through the monitoring experimental sites. The fourth seismic trace was oriented perpendicular to the local dip direction, developing along a terrace platform. P-wave seismic data were acquired with geophones positioned at regular intervals, whose position was detected by means of GNSS surveys (Figure A1.1). These devices are designed to detect ground vibrations with a natural frequency of 4.5–10 Hz and convert them into electrical signals (Figure A1.1).



Figure A1.1 - On the left, GNSS surveys for the acquisition of the array geometry. On the right, the arrangement of geophones (connected to the seismograph via cables) along a longitudinal seismic alignment.

The geophones are connected via cables to a multi-channel seismograph, which is the central unit for digital acquiring and recording signals from each geophone over time (acquisition time window of 0.25 sec) with a sampling frequency of 5,000 Hz. Once the acquisition alignments were defined and the geophones were positioned, seismic sources were regularly distributed along the seismic arrays. An 8 kg sledgehammer hitting a steel plate was employed as a seismic source.

A.1.2 Dynamic probing tests

To complement the seismic refraction surveys and gain more information on the soil thickness for an accurate geotechnical model, 7 dynamic probing tests were conducted along the seismic refraction alignments. Due to logistical issues concerning site accessibility and equipment transportation, these analyses were performed with a motor-driven medium dynamic

penetrometer (DPM), (Stefanoff et al., 1988), because of easily transportable on steep terraced slopes (D'Amato Avanzi et al., 2013).

The penetrometer used for the tests (Figure A1.2) has a 30 kg hammer mass, dropping from a height of 20 cm. By striking a 12 kg anvil, it drives the penetration of steel rods (1 m long and weighing 2.9 kg) into the ground. The progressive penetration of the rods into the ground is facilitated by a steel conical tip installed at the lower end (cross-sectional area of 10 cm², diameter of 35.7 mm, and apical angle of 60°).



Figure A1.2 - Dynamic probing test execution.

During penetration, the number of hammer blows required to advance the conical tip through the ground for each rod length of 10 cm (N_{10}) is recorded the test ended when the procedure continues until the ground's resistance becomes excessively high (i.e., $N_{10} \geq 50$), condition indicative of the bedrock occurrence. This measurement is then reported as the dynamic penetration index (DPI), expressed in millimetres per blow (mm/blow).

The initial analysis of the test results allows for the creation of N_{10} logs. These provide information on the layer thickness, helping in identifying the presence of layers with varying degrees of compaction based on their resistance to penetration. In order to evaluate the state of soils, N_{10} was normalized to the number of blows referred to the Standard Penetration Test (N_{SPT}) by means of a correlation factor taking into account the ratio between the specific energies per blow for the two test types (i.e., $N_{SPT} = \delta \cdot N_{10}$ with $\delta = 0.73$) (Odebrecht et al., 2005; D'Amato Avanzi et al., 2013). The empirical correlation between N_{SPT} and the relative density (DR) proposed by Gibbs and Holtz (1957) was then used.

A.1.3 Soil density tests

In the realm of in-situ geotechnical testing, the sand cone density test is a widely employed method for determining the in-situ density of both granular and cohesive soils. The primary objective of this test is to directly ascertain the total unit weight and dry unit weight of the soil in the field.

The test operates on the principle of volume replacement. A hole is excavated in the ground where the soil density is to be determined. The excavated material is weighed, and its moisture content is subsequently determined in laboratory. The volume of the excavated hole is then measured by filling it with calibrated sand of known density, which is allowed to flow from a cone apparatus. By knowing the mass of sand that filled the hole and its calibrated density, the volume of the hole itself can be calculated.

The Sand Cone Test procedure commences with the identification and preparation of a suitable area, which must be meticulously levelled and cleared of any stones, vegetation, or loose material. The base plate is then firmly seated upon the prepared surface. A regular test hole is carefully excavated through the base plate's circular aperture. Crucially, all excavated material must be collected and sealed immediately to prevent moisture loss, enabling accurate determination of its wet mass by subsequent weighing. Following excavation, the sand cone apparatus is assembled by attaching the cone to the bottle, which has been pre-filled and pre-weighed with calibrated sand. The complete apparatus is then positioned on the base plate. The valve is opened, allowing the sand to flow freely and completely fill both the excavated hole and the lower cone volume. Finally, once the flow ceases, the valve is closed, and the apparatus is removed. The volume of the test hole is subsequently calculated based on the mass of sand discharged (Figure A1.3).



Figure A1.3 - Soil density tests: a) hole excavated for the test; b) sand cone used for field analyses

Once the hole is filled, the sand remaining in the bottle is weighed to determine the actual quantity of sand required to fill the hole.

In laboratory, from the previously weighed excavated soil, a representative sample is taken for the determination of its moisture content (w). This sample is weighed (wet weight) and then oven-dried to a constant weight (dry weight).

In this way, by knowing the actual mass of sand in the hole and the known density of the calibrated sand, the volume of the hole itself can be determined. Based on the wet and oven-dried soil weights, and on moisture content, the dry and wet densities are finally calculated. In this work, 4 in-situ soil density tests were executed. The tests were carried close to the hydro-geotechnical monitoring instruments installed in each experimental site.

A.1.4 Double ring infiltrometer test

The infiltration test is an in situ hydrological investigation methodology that measures the vertical infiltration rate of the soil (e.g., mm/h). This parameter is essential for understanding the dynamics of water flow and the soil's water absorption capacity, allowing for the estimation of saturated permeability (K_{sat}), which is crucial for hydrogeological modelling. The test was performed in accordance with international (ASTM D3385-03) and national (DIN 19682) standards. The first step involves identifying a representative area of the soil to be tested, which should be as level as possible and free from dense vegetation, stones, or surface debris that could alter water flow.

The equipment consists of two concentric metallic cylinders of different diameters (in our case, an inner ring of 30 cm and an outer ring of 60 cm). The two rings are driven into the ground to a predetermined depth (approximately 15-20 cm) (Figure A1.4a), ensuring they are well-seated to prevent water leakage along the edges. To ensure uniform insertion and prevent deformation, a wooden plank and a hammer were used (Figure A1.4a). Once installed, both rings are filled simultaneously with water (Figure A1.4b).



Figure A1.4 – Double ring infiltrometer test: a) placement of the two concentric rings; b) initial condition in which both rings are simultaneously filled, maintaining the same water level.

The correct execution of the test requires maintaining a constant and uniform water level in both rings. The outer ring acts as a hydraulic barrier, saturating the surrounding soil and directing the water flow from the inner ring to an almost exclusively vertical percolation, thereby ensuring an accurate measurement of the infiltration rate. The measurement of the infiltration rate is obtained by timing the duration for a given volume of water to infiltrate, quantified by the drop in level within the inner ring. Measurements are initially frequent and become less frequent as the infiltration rate stabilises. The temporal trend shows a rapid initial decrease in the rate, which gradually attenuates until a near-constant value is reached when the soil achieves saturation and the flow becomes steady-state. This final value represents the saturated infiltration rate. The experimental data collected from the four conducted tests were used for the estimation of the soil's hydrological parameters through the application of two established semi-empirical infiltration models: the Horton model (1939) and the Philip model (1957).

A.2 SITE CHARACTERIZATION METHODS – LABORATORY INVESTIGATIONS

As a complement to the field investigations, laboratory tests were performed on soil samples taken in situ. The objective of these analyses was to characterise the physical and mechanical properties of the material sampled from the various sites under investigation.

A.2.1 Grain size analyses

The particle size distribution analysis is fundamental to determining a soil's texture by quantifying the dimensional range of its constituent particles. The procedure employs two principal methodologies, selected according to the particle diameter (d): sieving, utilised for

soil fractions with particle diameters exceeding 75 μm and sedimentation, employed for soil fractions with particle diameters smaller than 75 μm .

According to the guidelines of the Italian Geotechnical Association (AGI) (1994), the primary particle size classes are defined as follows: gravel ($200\text{mm} \geq d \geq 2\text{mm}$), sand ($2\text{mm} \geq d \geq 0.06\text{mm}$), silt ($0.06\text{mm} \geq d \geq 0.002\text{mm}$) and clay ($0.002\text{mm} \geq d$).

Before proceeding with the sieving process, given the significant quantity of material, the quartering technique was adopted.

Following the quartering operation, the sample is subjected to washing (wet sieving) for pre-selection of the material. This procedure separates the particles designated for Sieving ($d > 0.075\text{ mm}$) from those intended for Sedimentation ($d < 0.075\text{ mm}$). Subsequently, the coarser fraction (0.075mm) is oven-dried at a temperature of 105-110 $^{\circ}\text{C}$ for 24 hours.

Sieving process

Sieve analysis is a phase of particle size distribution analysis (also known as granulometric analysis) aimed at separating and quantifying soil particles with a diameter greater than 0.075 mm, which correspond to the gravel and sand fractions.

A dried soil sample is subjected to mechanical sieving using a vertical stack of standardized test sieves. The sieves are arranged in order of decreasing mesh opening, starting from the largest (e.g., 75 mm) at the top down to the smallest, typically the No. 200 sieve with an opening of 0.075 mm, which is positioned directly above a collecting pan (or receiver / base).

The mechanical agitation, lasting for 10 -15 minutes, ensures the material is classified by size, with the particles retained on any given sieve having a diameter between the sieve's own opening and that of the sieve immediately above it. At the conclusion of the sieving process, the material retained on each sieve is weighed precisely. This data allows for the calculation of the percentage by weight of the specific particle size fraction relative to the total initial mass of the sample. (Figure A1.5).



Figure A1.5 -Vibrating sieve used for sample screening.

Subsequently, the cumulative percentage passing for each sieve is determined, which represents the percentage by weight of the material with a diameter smaller than the sieve's opening. These values form the foundation for constructing the particle size distribution curve (or grading curve). The material collected in the collecting pan beneath the No. 200 sieve (particles with a diameter less than 0.075 mm) is designated for sedimentation analysis.

Sedimentation process

The sedimentation phase in granulometric analysis is employed to determine the particle size distribution of fine particles (silt and clay) with a diameter smaller than 0.06mm.

The isolated fine material is dispersed in distilled water to form a homogeneous suspension, which is then transferred to a 1000mL graduated cylinder. Following a vigorous initial re-suspension (time = 0), periodic measurements of the relative density of the soil-water mixture are conducted using a hydrometer at predefined time intervals (ranging from 1minute up to 24 hours). The underlying principle is the progressive settling of the larger particles, which causes a decrease in the density of the upper layer of the suspension. By applying Stokes Law, the equivalent diameter of particles that have settled below the measurement point within the considered timeframe is calculated. The resulting data allow for the determination of the percentage of particles finer than this diameter, thereby completing the particle size distribution curve initiated by sieving.

A.2.2 Atterberg limits

The Atterberg Limits define the state transitions of fine-grained soils as a function of water content, enabling their geotechnical classification. The Liquid Limit (LL) represents the water content above which the soil exhibits viscous behaviour and loses its shear strength. The Plastic Limit (PL) is the water content below which the soil ceases to be plastic and becomes a brittle solid. The Shrinkage Limit (SL) is the minimum moisture content beyond which no further volume reduction occurs upon drying. Fundamental indices are derived from the difference between these limits: the Plasticity Index ($PI = LL - PL$) quantifies the moisture range over which plasticity is exhibited. The Consistency Index ($CI = (LL - w) / PI$), where w is the natural water content, indicates the soil's consistency in its in-situ state relative to its characteristic limits. The determination of these limits, in compliance with standards such as ASTM D4318, necessitates preliminary sample preparation, involving the isolation of the fraction passing the 0.425 mm sieve (No. 40 sieve) and its thorough mixing with distilled water to achieve the appropriate consistency for testing.

Liquid Limit (LL) determination

The Liquid Limit (LL) is defined as the water content at the transition boundary between the viscous-liquid state and the plastic state of a fine-grained soil. The determination is carried out using the Casagrande apparatus. The standard procedure involves placing a soil paste with a uniform thickness of approximately 1 cm in the cup of the apparatus, followed by the incision of a central groove (Figure A1.6). The number of blows (N) required for the two soil masses to close over a length of 13 mm is recorded. Subsequently, the water content (w) corresponding to the groove closure is determined. The test is repeated, modifying the water content (w) to obtain a range of N between 15 and 35 blows. The Liquid Limit (LL) is the value of w corresponding to $N = 25$ blows, which is extrapolated from a flow curve plotted on a semi-logarithmic graph (with w on the linear scale and N on the logarithmic scale).



Figure A1.6 - Casagrande cup used for determining the liquid limit.

Plastic Limit (PL) determination

The Plastic Limit (PL) identifies the water content below which the soil ceases to exhibit plastic behaviour, transitioning into a semi-solid state.

The methodology involves manually rolling a portion of the hydrated soil sample into a thread on a non-absorbent surface. The limit is reached when the thread begins to fissure and crumble upon reaching a critical diameter of 3 mm. At this point, the water content of the fragmented soil is measured by oven drying. The final PL value is established as the arithmetic mean of a minimum of three replicated determinations on the same sample. Once the Liquid Limit (LL or WL) and the Plastic Limit (PL or WP) have been determined, the Plasticity Index (PI) can be calculated. The PI represents the range of water content over which the soil exhibits plastic behaviour and is a fundamental parameter for the geotechnical classification of fine-grained soils. Its determination uses the following formula:

$$IP = Wl - Wp \quad (43)$$

3.2.3 Specific gravity

The Specific Gravity of Soil Solids (G_s) is a fundamental dimensionless coefficient in geotechnics, defined as the ratio between the density of the soil's solid phase (ρ_s) and the reference density of distilled water (ρ_w) at 20 °C. This parameter directly reflects the average mineralogical density of the soil particles. Its laboratory determination is conducted using the

pycnometer method, in compliance with the standard UNI EN ISO 17892-3:2016, applicable to samples with a maximum grain size $\leq 4\text{mm}$. The underlying principle is the precise measurement of the volume occupied (V_s) by a known dry mass (M_s) of soil particles, which is indirectly derived from the volumetric displacement of water. The protocol mandates oven-drying the sample at $105 \pm 5^\circ\text{C}$ to constant mass. After ascertaining the dry mass (M_s) and the mass of the empty pycnometer (M_p), the sample is transferred and subjected to intensive de-aeration (typically via stirring and heating). This is a critical step to eliminate occluded air bubbles that would otherwise lead to an overestimation of V_s . Upon cooling to 20°C and filling the pycnometer to its nominal volume, three essential mass measurements are recorded for the final calculation: the mass of the pycnometer with solids and water (M_{psw}), the mass of the empty, dry pycnometer (M_p), and the mass of the pycnometer filled only with water (M_{pw}). The processing of these data allows for the calculation of the solid density (ρ_s) and, consequently, G_s . This procedure was methodically applied to all four soil samples collected in situ (S1, S2, S3, and S4), which are considered representative of the three investigation sites. Based on the mass information obtained from the test, the specific gravity for each analysed sample is calculated using the following formula.

$$G_s = \frac{M_s}{(M_{pw} - M_p) - (M_{psw} - M_s)} \quad (44)$$

M_s = Mass of dry soil sample (g)

M_p = Mass of empty pycnometer (g)

M_{pw} = Mass of pycnometer filled with water only (g)

M_{psw} = Mass of pycnometer with soil and water (g)

A.2.4 Organic content

Determining the soil organic content is a crucial analysis, as its percentage profoundly influences the soil's physical, chemical, and biological properties, particularly its water-holding capacity.

The standard method adopted for this analysis is Loss-on-Ignition, conforming to ASTM D2974 standards. This principle relies on the direct correlation between a sample's weight loss, following high-temperature heating (calcination), and the oxidation/volatilisation of the organic

matter. The analytical procedure involves an initial drying of the sample in an oven at 105 °C for 24 hours to eliminate hygroscopic water while preserving the organic matrix. The weight obtained after drying is recorded as the initial weight (P_i). Subsequently, the sample is calcinated in a muffle furnace at approximately 450°C for 6 hours, a process which converts the organic matter into gases (CO_2 and H_2O). After cooling in a desiccator, the final weight (P_f) is determined.

The percentage of organic matter is then calculated as the weight loss relative to the initial weight, according to the following expression:

$$O.C. (\%) = \left(\frac{P_i - P_f}{P_i} \right) 100 \quad (45)$$

APPENDIX 2

RESULTS OF EXPERIMENTAL SITE CHARACTERIZATION

This chapter presents the preliminary results of the site's geotechnical characterisation, conducted as part of the “Stone Wall for Life” project. This characterisation, carried out through in situ and laboratory testing, pursues the primary objective of defining a reliable geotechnical model for the area of interest.

IN-SITU TEST RESULTS

During the excavation of the trench for the installation of the sensors, it was possible to conduct a survey and analysis of the soil profile. The most relevant aspects and distinctive characteristics of the soil horizons identified are listed below.

- Experimental site 846

At the investigated site, the bench of the terrace is covered by dense shrub vegetation mainly constituted of *Erica arborea*. The soil profile (Figure A2.1) presents the following horizons: O (0-3 cm), A1 (3-45 cm), A2 (45-80 cm), and C (80 cm - not observed limit). The limit between O and A1 is linear and abrupt (0.5 cm thick); the one between A1 and A2 is irregular and blended (5-10 cm thick); that between A2 and C is irregular and abrupt. In O, A1, and A2 horizons no pedogenetic features were observed. The soil structure is granular; aggregates are subangular and polyhedral with prevalent size of 2-5 mm. Pores are > 5% and essentially < 2 mm. Cracks were not observed in O and they were very rare and < 1 cm wide in A1 and A2 horizons. No evidence of biological activity is documented. Few (20-50 in 1 dm²) roots < 2 mm and none > 2 mm characterize O; common (50-200 in 1 dm²) roots that are both < 2 mm and > 2 mm characterize A1, and few (20-50 in 1 dm²) roots < 2 mm and none > 2 mm characterize A2. Root size refers to the diameter. In essence, the investigated soil is weakly developed (young) and anthropogenically reworked, lacking diagnostic horizons and thus most likely attributable to the Regosol typology (Classification WRB).



Figure A2.1 – Soil profile within the trench pit excavated at the abandoned terraced site.

- Experimental Site 915

The soil profile (Figure A2.2) presents the following horizons: A1 (0-30 cm), A2 (30-55 cm), and C (55 cm - not observed limit). The limit between A1 and A2 is irregular and blended (5-10 cm thick), while that between A2 and C is linear and abrupt (1 cm thick).



Figure A2.2 – Soil profile within the trench pit excavated at the cultivated terraced site.

In A1 and A2 horizons, no pedogenetic features (e.g., mottles, slickensides, nodules, and concretions), and very rare aggregates (2-5 mm) were observed; moreover, the skeleton is composed of non-altered angular/very angular clasts. The soil structure is granular. Cracks were not observed, and no evidence of biological activity is documented. Pores are very abundant (< 0.5 mm) and common (0.5-2 mm) in A1 and very abundant (< 0.5 mm) and few (0.5-2 mm) in A2. The main difference between A1 and A2 horizons is represented by root distribution. Roots

< 2 mm are common (50-200 in 1 dm^2) and > 2 mm are absent in A1, while there are few (20-50 in 1 dm^2) roots (both < 2 mm and > 2 mm) in A2. Root size refers to the diameter.

It should be noted that the profile of the trench pit excavated at the monitoring station installed in Site 850 has not been described. At this site, soils resulted completely reworked following dry-stone wall construction phases, making the soil profile description meaningless from the pedological point of view.

P-waves seismic refraction

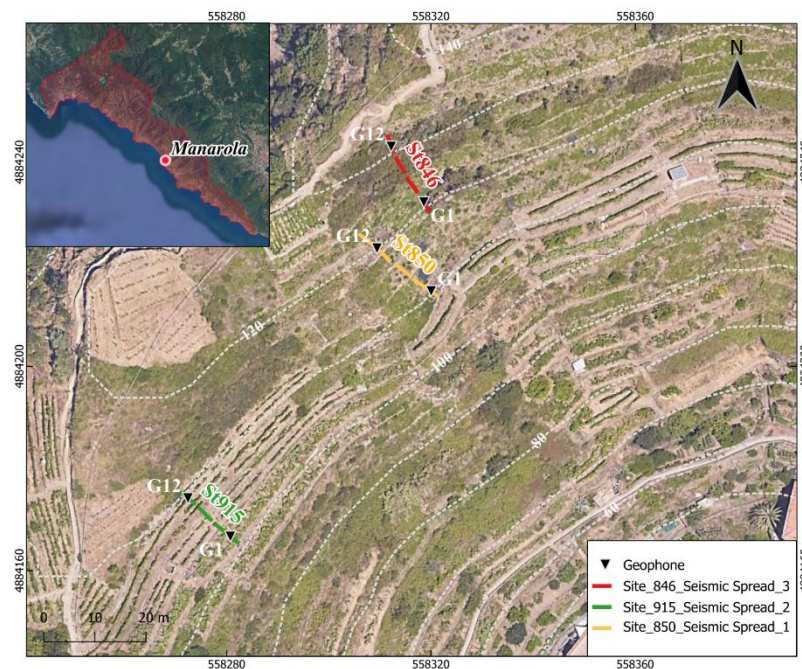


Figure A2.3 - Location seismic alignments (the geophones positioned at the array edges are shown).

Three longitudinal seismic surveys were carried out at each experimental site along the maximum slope dip direction and along the same alignments as the DP tests (Figure A2.3). At Site 846 and Site 915 20 m long seismic arrays were deployed, and an average spacing of 1.5 m between geophones was adopted. At Site 850, an approximately 28 m long seismic array was employed, with an average geophone spacing of about 2 m.

The outcomes of seismic refraction survey consisted of tomographic profiles showing the distribution of seismic waves below the ground level. These profiles enabled the differentiation between the superficial soil cover and the underlying bedrock (Figure A2.4).

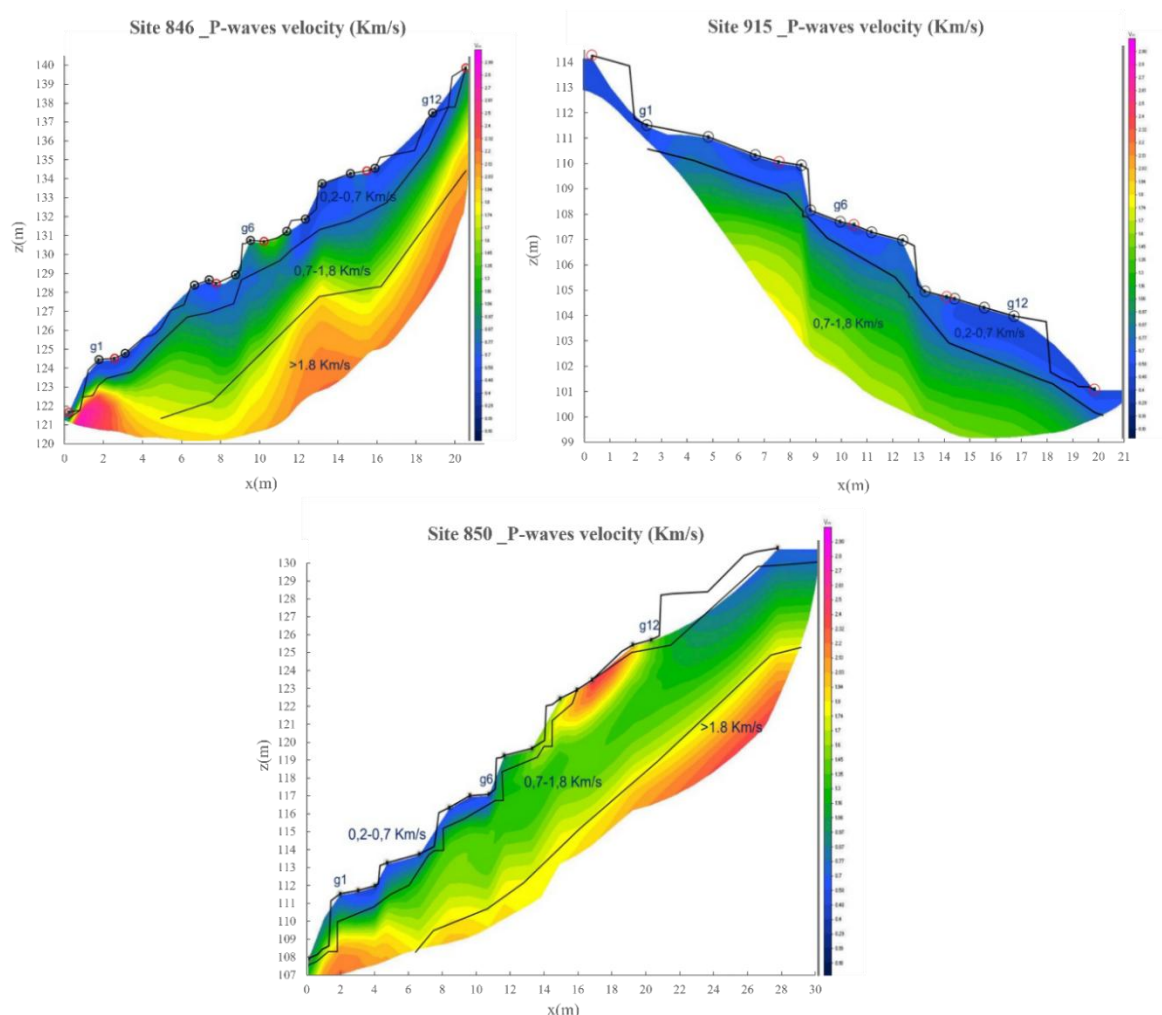


Figure A2.4 - P-wave seismic refraction tomography profiles.

The results of the seismic refraction survey allowed for the classification of the subsurface into three main homogeneous seismic-stratigraphic horizons, which reflect variations in the geomechanical properties of the materials allowing a preliminary lithostratigraphic interpretation.

The results highlighted a general increase with depth, indicative of rising compaction and rigidity, as follows:

- **Horizon 1 - Low P-wave velocity (0.2–0.7 km/s):** corresponding to shallow soil layer (thickness $\approx 1.5 - 2$ m) composed of loose or poorly consolidated materials that could be referred to the aerated and reworked eluvial-colluvial soils.
- **Horizon 2 - Medium P-wave velocity (0.7–1.8 km/s):** range that may indicate a more compact soil that gradually increase in compaction up to the contact with the weathered/fractured bedrock.

- **Horizon 3 - High P-wave velocity (>1.8 km/s):** horizon that could be referred to the rigid un-weathered bedrock.

Dynamic probing tests

In accordance with the procedures outlined in paragraph A.1.2, seven dynamic cone penetrometer tests were carried out (Figure A2.3). Specifically, three tests were conducted at Site 850 (PP5, PP6, PP7), while the remaining four were equally distributed between Site 915 (PP3, PP4) and Site 846 (PP1, PP2) (Figure A2.5).

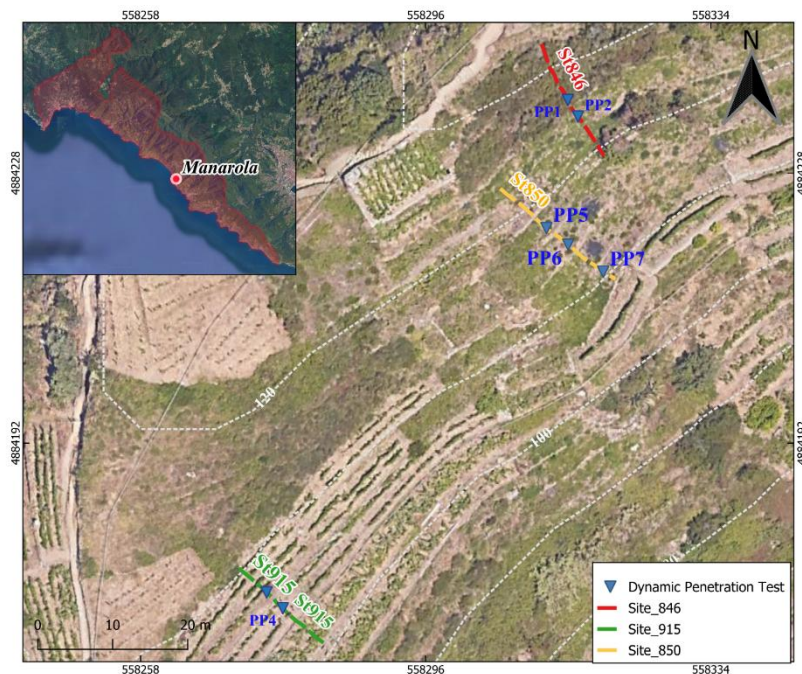
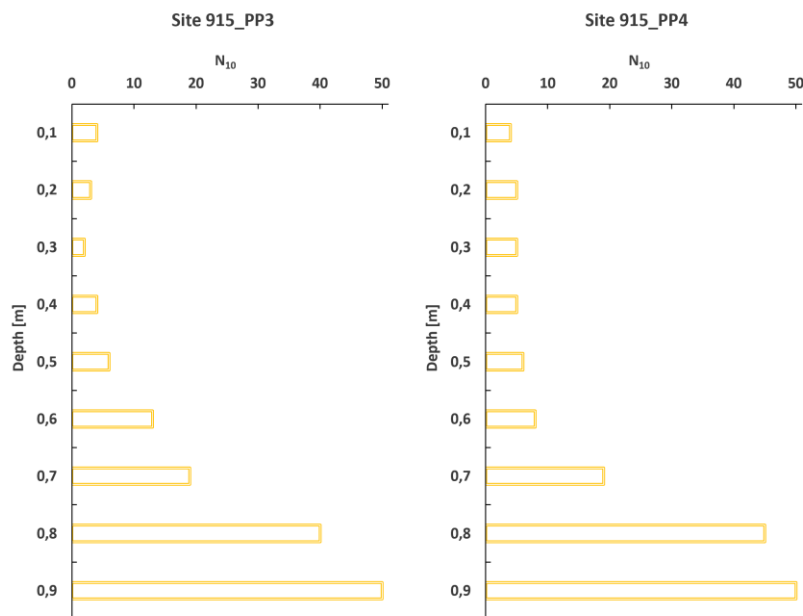
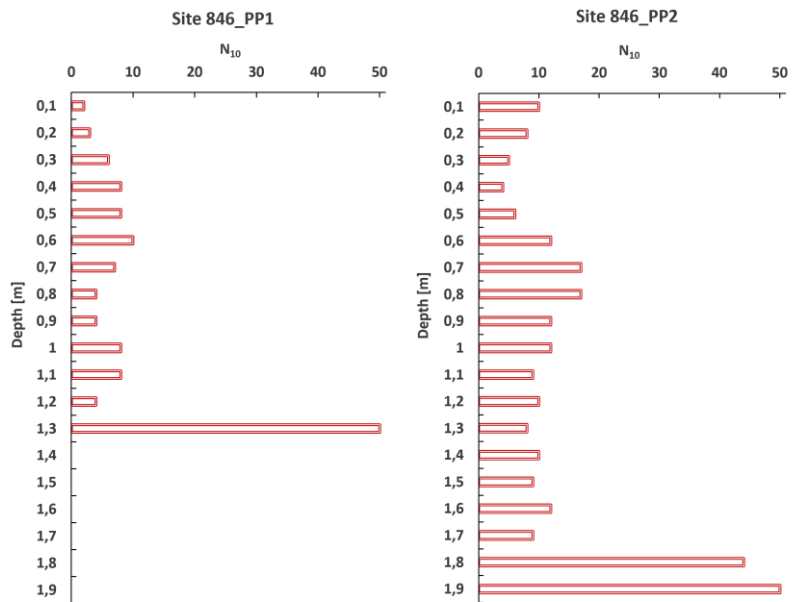


Figure A2.5 - Location of dynamic penetrometer tests.

The test results were used to create dynamic penetration profiles (N_{10} vs. depth); (Figure A2.6). These logs provided key information on soil thickness and on the stratigraphic frame.



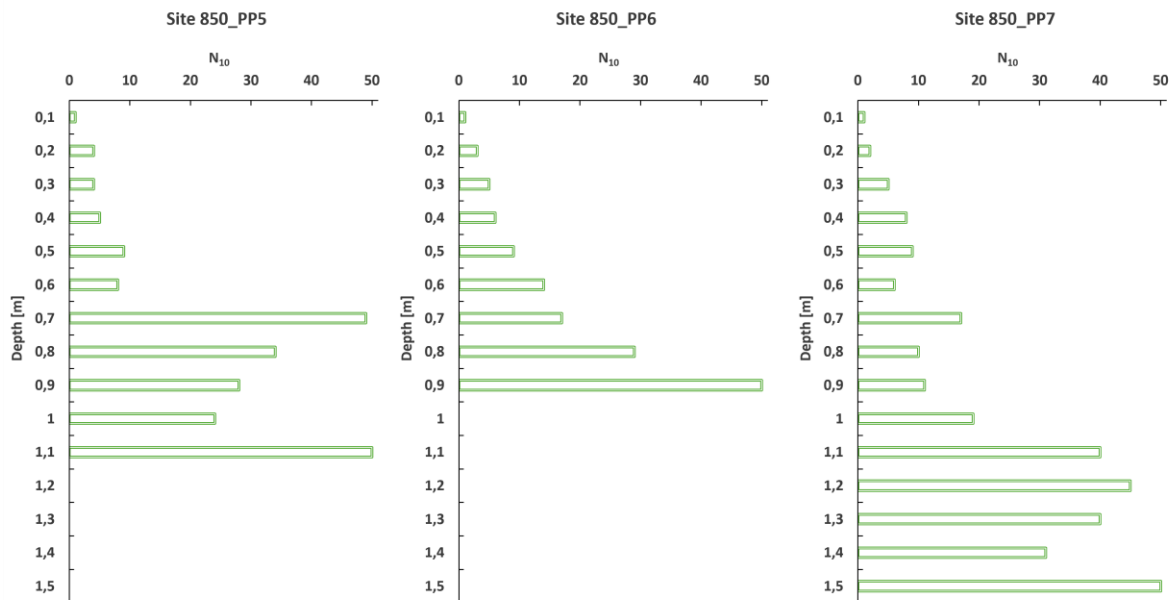


Figure A2.6 - Dynamic probing test results: N_{10} vs. depth profiles.

In general, DP test outcomes show a progressive increase in the number of blows with depth, highlighting a general increase in soil density. In some tests, a certain variability in the N_{10} – depth profiles was found, likely associated to the presence of clasts dispersed within the soil matrix. Indeed, some profiles show jagged trends of the N_{10} values that could reveal the presence of pebbles. The results are in good agreement with those obtained from indirect geophysical investigations.

The analysis of N_{10} vs. depth profiles revealed the following subsoil stratigraphy:

Site 846: it exhibits a uniform cover of an average thickness of approximately 1.6 m, characterised by poor compaction (i.e., low N_{10}). The transition to the bedrock is sharp and distinct, indicating a well-defined interface (Figure A2.6).

Site 915: the soil cover-bedrock transition is gradual, highlighting a progressive increase in material penetration resistance (N_{10}) with depth and suggesting the presence of a single layer that progressively becomes more compact with depth.

Site 850: the superficial layer (0.1 m - 0.5-0.6 m thick) shows very low N_{10} values, indicating very loose and poorly compacted soil. At varying depths (approximately between 0.7 m and 1.0 m), a rapid increase in N_{10} is observed, indicating the presence of more compact layers. The depth of the bedrock varies between 1.1 m and 1.5 m.

Soil density test

In accordance with the standard procedures described in paragraph A.1.3, four in-situ density tests were conducted using the sand cone method. Specifically, the tests were distributed as follows: two at Site 850 (identified as D2 and D3), one at Site 915 (D4), and one at Site 846 (D1) (Figure A2.7).

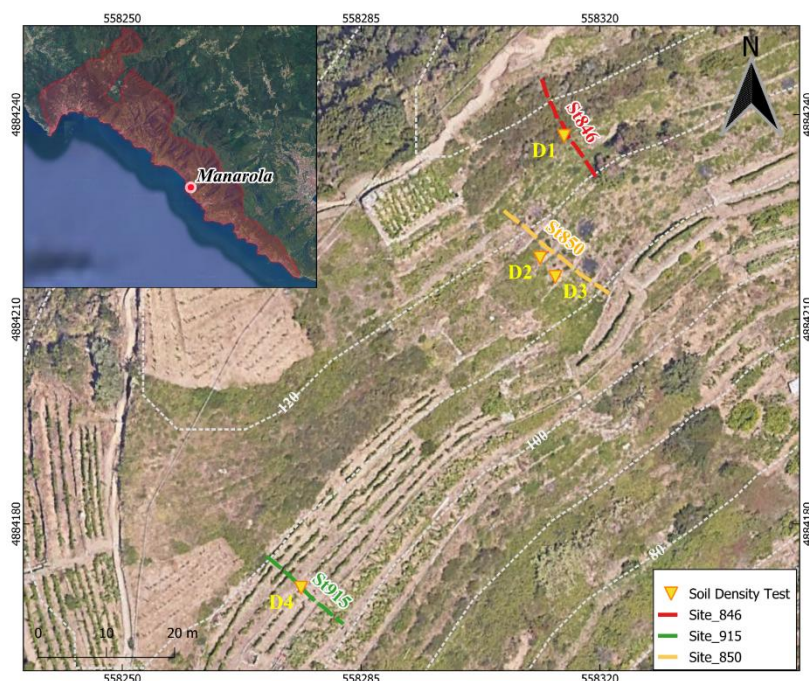


Figure A2.7 - Location of soil density tests.

Analysis of the measurements obtained from the sand cone tests allowed for the determination of the unit weight of the material in its natural/moist (γ_{nat}), dry (γ_{dry}), and saturated (γ_{sat}) states, in addition to the natural moisture content (w_n) (Table A2.1).

Table A2.1- Summary of in-situ density test results.

Site	ID	γ_{nat}	γ_{dry}	γ_{sat}	w_n
		kN/m ³	kN/m ³	kN/m ³	%
850	1	12,5	12	17,2	4,4
	2	14	13,3	18,4	5,3
846	3	14,9	14,6	19,1	2,2
915	4	15,9	15,3	19,5	3,9

The penetrometric survey results indicated a variation in soil density with depth. Specifically, a less dense superficial layer (referred to as "Cover 1") and a deeper, more compact layer

(termed "Cover 2") were identified. Consequently, the parameters of angle of internal friction and relative density were distinctly considered for each of these two stratigraphic units.

Table A2.2 - Relative density and angle of internal friction parameters derived from empirical correlations.

	D_r (%) (Gibbs & Holtz 1957)	D_r (%) (Cubrinowski & Ishihara, 1999)	ϕ' (°) (De Mello, 1971)	ϕ' (°) (Shioi & Fukuni, 1982)	ϕ' (°) (Japanese National Railway, 1990)
	Average	Average	Average	Average	Average
Cover 1	20	30,5	25	29	25
Cover 2	26,5	63	30	33,5	32,5

Double ring infiltrometer test

In accordance with the procedure described in paragraph A.1.4, three double-ring infiltrometer tests were conducted. To ensure the data were representative of different land-use conditions, two tests (DRI1, DRI2) were performed on a cultivated terraced vineyard, while the third test (DRI3) was carried out on an abandoned agricultural terrace near Site 846 (Figure A2.8). Each test lasted between 1.0 and 1.5 hours.

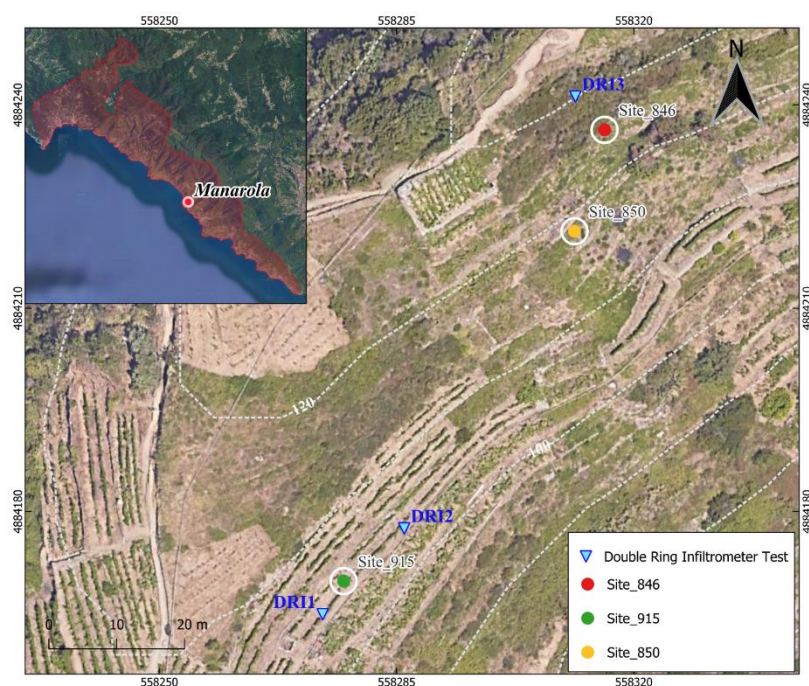


Figure A2.8 - Location of double ring infiltrometer test.

The field-measured infiltration capacity data obtained were subsequently fitted by using two established mathematical models: the Horton model (Horton 1939) and the Philip model (1957). This process was undertaken to identify the best-fit model for each dataset, thereby enabling

the direct determination of saturated permeability (k_{sat}) from the following empirical correlations (eq. 46, 47):

$$f(t) = f_c + (f_0 - f_c)e^{-kt} \quad \text{Horton (1939)} \quad (46)$$

$$f(t) = \frac{S}{2\sqrt{t}} + A \quad \text{Philip (1957)} \quad (47)$$

where:

f_0 = initial infiltration capacity

f_c = final or saturated infiltration capacity

k = decay constant

S = sorptivity

A = saturated infiltration rate

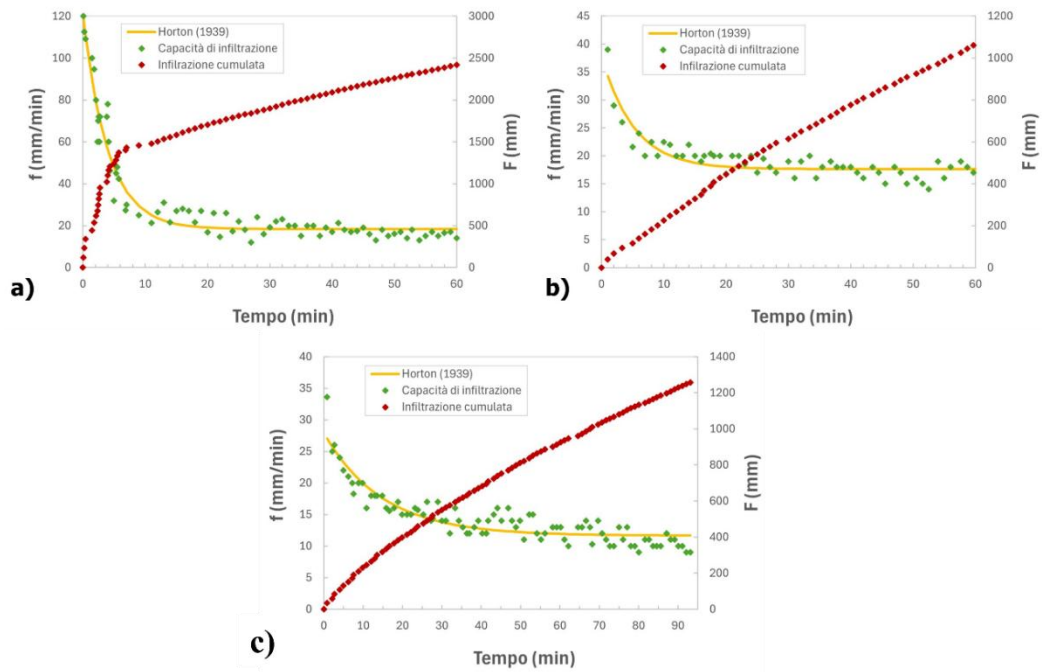


Figure A2.9 – Experimental data (f = infiltration capacity; F = cumulative infiltration) and best-fit curves of infiltration capacity using the theoretical Horton model: a) test DRI1, b) test DRI2, c) test DRI3.

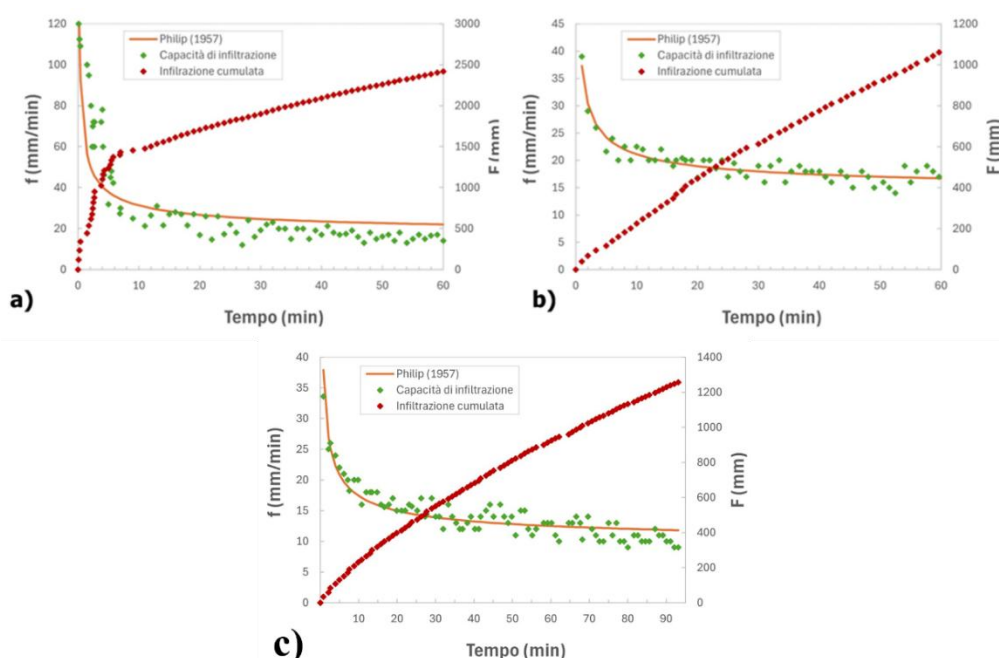


Figure A2.10 – Experimental data (f = infiltration capacity; F = cumulative infiltration) and best-fit curves of infiltration capacity using the theoretical Philip model: a) test DRI1, b) test DRI2, c) test DRI3.

Both empirical models accurately captured the characteristic rapid decreasing trend occurring during the initial stages of the infiltration process, subsequently followed by a stabilising phase at a near-constant value at the final test stages (Figures A2.9 and A2.10). A subtly distinct infiltration behaviour is observed among the different tests (DRI1, DRI2, DRI3), reflecting specific site conditions. Notably, the test DRI1 exhibits the highest initial infiltration capacity. Despite the variations in the slope of the initial decay curve, all tests converge towards a relatively similar final infiltration capacity, ranging from approximately 5 to 15 mm/min. These values are indicative of a comparable saturated permeability for the tested soils once they have reached a state of saturation. This further suggests that, in the long term, a similar capacity of these soils to transmit water through their saturated pores.

As shown in Table A2.3, the returned values of k_{sat} are consistent in terms of order of magnitude across the different tests and the two mathematical models.

Table A2.3 - Summary of best-fit results from infiltration test data using the Horton and Philip models (f_0 = initial infiltration capacity, f_c = final or saturated infiltration capacity; k_s = saturated permeability, k = decay constant, S = sorptivity, RMSE = Root Mean Square Error, MAE = Mean Absolute Error).

Test n.	Horton (1939)						Philip (1957)				
	f_0 (mm/min)	f_c (mm/min)	k_s (m/sec)	k (min ⁻¹)	RMSE	MAE	S (mm/min ^{-0.5})	k_s (mm/min)	k_s (m/sec)	RMSE	MAE
DRI-1	121,5	18,4	3,10E-04	0,25	5.9	4.3	99,3	15,6	2,60E-04	14.0	9.8

DRI-2	37,8	17,6	2,90E-04	0,19	1.8	1.5	47,2	13,7	2,30E-04	1.4	1.2
DRI-3	27,9	11,7	1,90E-04	0,07	1.7	1.3	52,7	9,1	1,50E-04	1.6	1.4

This indicates a relative uniformity in the saturated hydraulic properties of the investigated soils. Consequently, the average saturated permeability, determined for the topsoil (i.e., thickness of 15-20 cm) in the study area, stands at approximately 2.39×10^{-4} m/s. These values are well consistent with those obtained in other studies dealing with the geotechnical characterization of terraced soils at Cinque Terre (Cevasco et al., 2013; Cevasco et al., 2014) those obtained through numerical simulations (Schilirò et al., 2023; Fiorucci et al., 2023).

4.2 LABORATORY TEST RESULTS

Four undisturbed soil samples were retrieved: samples S1 and S2 at Site 850, sample S3 at Site 915 and sample S4 at Site 846 (Figure A2.11).

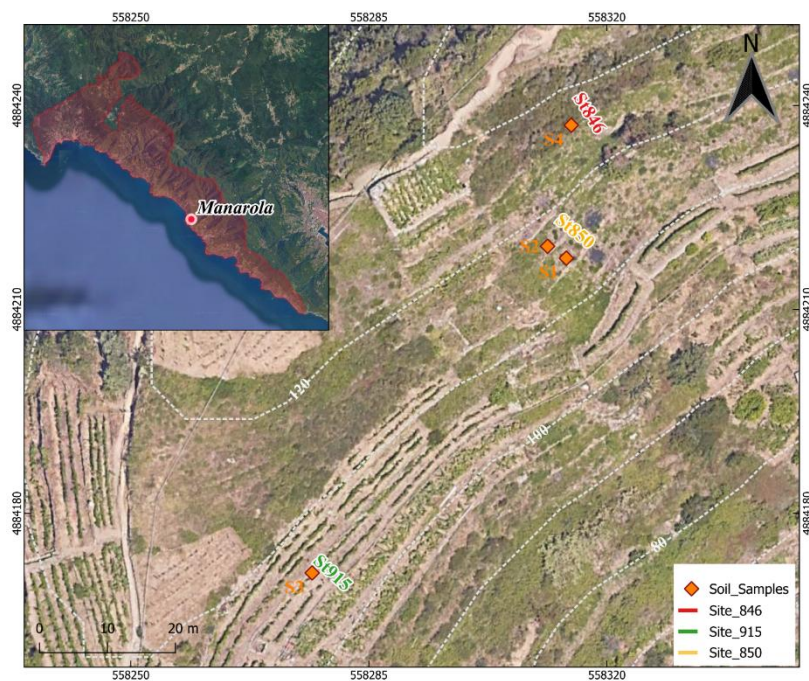


Figure A2.11 - Sampling locations for laboratory tests.

Grain size analysis

The granulometric analysis was carried out in the laboratory in accordance with the standard procedure described in section A.2.1 and the results are presented in Figure (A2.12) as particle size distribution curves.

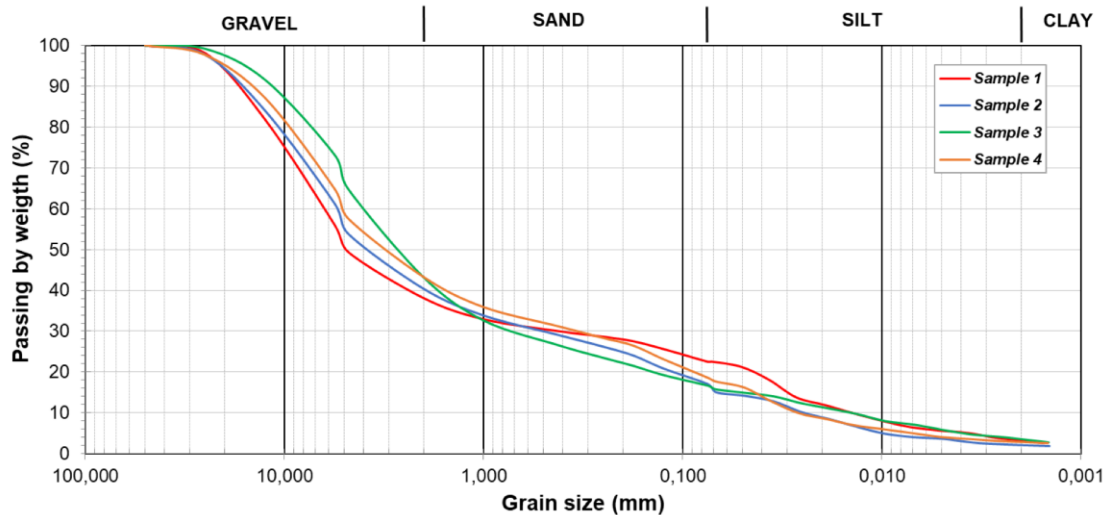


Figure A.12 - Results of the grain size distribution for the four samples.

The particle size analysis of the samples reveals a significant presence of gravel and coarse sand. Notably, the sample identified by the green curve (Sample 3) exhibits a lower percentage of gravel compared to the other analysed samples (Table A2.4). The patterns of such curves denote that the soils at the monitoring sites resulted poorly sorted and non-uniform from a granulometric point of view. The coefficient of uniformity resulted very high (Table A2.4), with values greater than 100, quantitatively confirming that the sampled soils are very poorly sorted. It can be noted that the patterns of the various grain size curves are very similar, even if some slight differences in the percentages of some grain size classes occur. The maximum diameter of soil particles resulted approximately 40 mm. The average particle size (D_{50}) resulted comprised between 3.0 and 4.75 mm. The shape of clasts was found to be from lamellar to elongated and from angular to sub-angular. Moreover, the soil granules resulted weak and often easily crumbled by hand. These features clearly reflect the intrinsic fissility of the original rock types.

Regarding the finer fractions, all samples contain a non-negligible percentage of silt, although significantly less abundant than the coarser fractions. The percentage of clay sediments is minimal, indicating a very low incidence of clay in the samples (Table A2.4). It is important to note that there are similarities between the samples in terms of fines content (i.e., percentage of soil passing through the sieve n°200), showing an average value of 18.7%.

In light of these results, the material can be classified as well-graded and characterised by a high overall percentage of gravel and sand. This particle size composition, dominated by coarse fractions, is indicative of good drainage characteristics, especially under saturated conditions.

Based on these particle size percentages, the soil samples have been classified using the U.S.C.S. (Unified Soil Classification System) (Table A2.4).

Table A2.4 – Summary of particle size percentages for the different samples.

Site	ID	Gravel	Sand	Silt	Clay	U.S.C.S.
		%	%	%	%	
850	Sample 1	50,7	26,8	19,4	3,1	GM
	Sample 2	46,3	36,7	14,9	2,1	SM
846	Sample 3	35,4	48,1	13	3,6	SM-SC
915	Sample 4	42,6	38,9	15,7	2,9	GM

According to the U.S.C.S classification, the soil samples were silty gravels (GM), silty sands (SM) and silty-clayey sands (SM-SC). These results agree with those obtained from other laboratory investigations conducted on terraced soils in the Cinque Terre (Cevasco et al., 2013b; Cevasco et al., 2014) and from zones of the Liguria region with similar geological and geomorphological settings (Cevasco et al., 2017; Vannucci et al., 2019).

Atterberg limits

Table A2.5 summarises the results of Liquid Limit, Plastic Limit, Plasticity Index, and natural water content for the soil samples collected at sites 850, 915, and 846.

Table A2.5 – Summary of Atterberg limits laboratory tests.

Site	ID	W _L	W _P	IP	w _n
		%	%	%	%
850	Sample 1	28	23,1	4,9	4,4
	Sample 2	34,3	n.d.	n,d	5,3
846	Sample 3	25,3	20,8	4,5	2,2
915	Sample 4	24,2	20,6	3,6	3,9

The low percentages of fine-grained soils significantly influence the soil plasticity, resulting from low to null. The Plasticity Index (PI) values obtained for samples 1, 3, and 4 are low, basically below 5%, indicating that the fine fractions are predominantly low-plasticity silts (ML) and organic silts and clays (OL) of low plasticity. (Figure A2.13). The low plasticity suggests that these materials may have a limited capacity to undergo significant plastic

deformations and might exhibit mechanical characteristics assimilable to those of granular soils, particularly in terms of compressibility and shear strength.

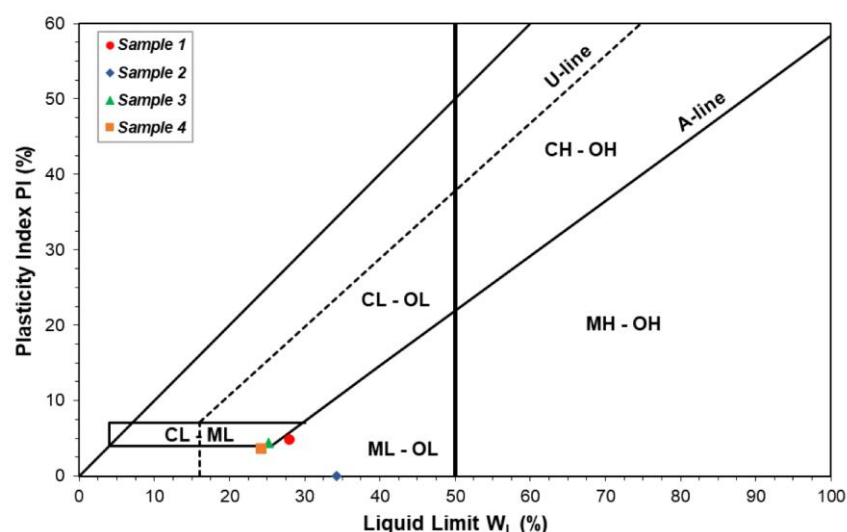


Figure A2.13 - Casagrande Plasticity Chart showing the classification of the four soil samples.

In general, the low plasticity of samples can be attributed to the low content of clay and clay minerals, which is consistent with the nature of the underlying arenaceous bedrock.

Physical soil properties

The laboratory test to determine the specific gravity (G_s) was performed on the analysed samples according to the standard procedure outlined in section A.2.3. This parameter is fundamental for calculating other physical and mechanical properties of the soil, such as the void ratio (e) and porosity (n) (Table A2.6).

Table A2.6 - Summary of physical soil properties for the collected samples.

Site	ID	G_s	γ_d	e	n
		-	kN/m^3	-	-
850	Sample 1	2,59	12	1,11	0,53
	Sample 2	2,83	13,3	1,08	0,52
846	Sample 3	2,76	14,6	0,85	0,46
915	Sample 4	2,74	15,3	0,76	0,43

The total porosity of the four samples ranges from 43% to 53%, indirectly reflecting the soil's state of compaction. These values are well consistent with the granulometric features, thus suggesting mechanical and hydraulic properties behavior that can be referred to coarse-grained

and cohesionless materials. The results obtained from the determination of the percentage of soil organic matter are summarised in Table A2.7.

Table A2.7 - Organic matter content (O.C.) for the analysed soil samples.

Site	ID	O.C.
		%
850	Sample 1	6.0
	Sample 2	10.0
846	Sample 3	4,4
915	Sample 4	3,4

An average percentage of organic matter equal to approximately 6,0% was found. Notably, at Site 850, OC values reached 10%, indicating high percentage of organic matter and a fertile soil, thus exhibiting a high-water retention capacity. Conversely, this can imply significantly lower mechanical strength and increased compressibility. However, it should be remarked that the analysed soils were collected in terraced site which have been abandoned from several decades and that was covered by a dense Mediterranean scrub vegetation. The same as for the site 846 (OC 4.4%).