The effects of layering on triggering mechanisms of rainfall-induced landslides in unsaturated pyroclastic granular soils

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The effects of layering on triggering mechanisms of rainfall-induced landslides in unsaturated pyroclastic granular soils.

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Draft

Abstract

Rainfall-induced landslides are widespread in shallow layered granular soil deposits. In many cases, slope instability is related to the decrease of suction during rainwater infiltration. However, the contrasts in the unsaturated hydraulic properties of the soils deeply affect the infiltration process, thus influencing slope failure. Coarse-textured soil layers embedded between finer ones may initially confine the process within the overlying finer layers, delaying the infiltration and eventually inducing lateral flow diversion. Nonetheless, depending on the state variables at the beginning of rain as well as on rainfall characteristics, the coarser layers may have or not a positive effect on stability. The results of a research based on advanced geotechnical characterization, physical and numerical modeling and field monitoring have been analyzed to investigate the effects of layering on slope stability.

Key words: **layered soil deposits, capillary barrier, physical modeling, field monitoring.**

1. Introduction

Rainfall-induced landslides in granular soils are widely diffuse in the world and undergo growing attention due to their frequency and, now even more, to climate change. Despite the great effort made to hinder them, they are still a recurring natural hazard resulting, every year, in many fatalities and property damages (Jakob and Hungr 2005; Sidle and Ochiai 2006).

Along steep slopes, the shallow covers usually rest in unsaturated conditions and the failure mechanism, under rainwater infiltration, primarily involves the wetting front advancement, which causes suction loss, in turn leading to a decrease in soil shear strength. Thus, slope stability which is directly linked to the pore water pressure distribution within the slope, is a function of infiltration rate, soil hydraulic and mechanical characteristics, and slope geometry (Alonso et al. 1995; Collins and Znidarcic 2004; Eichenberger et al. 2011; Hossain et al. 2013). In some cases, also the post-failure evolution of the soil mass, which may experience a complete fluidization turning into a very rapid and destructive flowslide

(Hutchinson 1988; Hungr 2001), is related to the degree of saturation of the soil at the onset of the instability (Damiano and Olivares 2010). Therefore, assessing the hydrological response of unsaturated slopes subjected to rainfall is critical and challenging (Baeza and Corominas 2001; Godt et al. 2009; Lee and Park 2015; Morse et al. 2014). In presence of soil layering, this task becomes even more complicated owing to the different mechanical and hydraulic properties of each soil horizon and, even more, to the non-linear hydraulic response of the entire stratigraphic sequence which changes during the progressive saturation.

Layered soils are ubiquitous and exhibit vertical textural contrast as a result of their natural or anthropogenic formation. In some cases, as in residual soils, the weathering process responsible for the creation of soil horizons from a single parent material, brings to a soil profile characterized by a continuous and gradual vertical variation of hydraulic and mechanical soil properties (Little 1969; Rahardjo et al. 2004). In other cases, as in air-fall pyroclastic deposits, due to their mode of formation, transportation and deposition, strong

vertical contrasts in texture occur, leading to abrupt variation of the properties of adjoining layers, as coarser and finer materials often alternate within the stratigraphical sequence. Such discontinuities affect the infiltration process by limiting the downward water flow and increasing soil water storage capacity of the upper layers by means of two mechanisms (Alfnes et al. 2004), usually indicated as “capillary” and “hydraulic barriers”.

A capillary barrier effect may develop in layered unsaturated systems characterized by strong textural contrast when a relatively fine-grained material overlies a coarse soil (Miyazaki 1988; Shackelford et al. 1994; Stormont and Anderson 1999). In an initially dry soil profile, during rain water infiltration (Fig. 1), at the interface between the two materials, sharing similar suction, the lower unsaturated hydraulic conductivity of the coarser soil hinders the downward leakage of water from the overlying fine-grained layer, resulting in a water storage within the upper fine layer higher than the level that would be normally attained under gravity drainage (Si et al. 2011).

The term “hydraulic barrier” is often used in presence of saturated water flows where a relatively coarse-grained soil overlies a finer material characterized by low permeability. It is also used in unsaturated conditions (Hillel 1982; Scott 2000). In presence of a coarse over fine soil sequence and in a very wet soil profile, as the unsaturated hydraulic conductivity of the coarse layer is higher than that of the underlying finer one (Fig. 1), at the interface between the two layers the infiltration rate is controlled by the finer soil, so that water may accumulate in the overlying coarse layer. Hence, the actual establishment of both capillary and hydraulic barriers is caused by the contrast of the hydraulic conductivity of adjoining layers, which, in unsaturated conditions, strongly depends on the wetting state of the soil. Thus, in unsaturated granular covers characterized by complex stratigraphical sequences with alternating coarse and fine-textured soil layers, both capillary and hydraulic barriers may develop (or not) at different stages of the same rainfall infiltration event. This paper first recalls the main results of previous investigations on the effect of layering on infiltration in shallow

sloping deposits. Then, the case study of a regularly layered granular cover of air-fall pyroclastic origin is analyzed by means of field monitoring and of physical and numerical modelling: to this aim experimental and numerical results are exploited.

Despite the particular nature of the investigated soils, the research allowed examining the main characteristics of rainwater infiltration into layered granular deposits, the role played by the initial conditions, and the potential effects on slope failure triggering.

2. The effect of layering on infiltration through shallow sloping soil deposits

The capillary barrier effect has been widely exploited to realize cover systems in waste disposal sites (Khire et al. 2000; Tami et al. 2004; Aubertin et al. 2009; Abdolazadeh et al. 2011) in arid and semi-arid regions and, more recently, for slope stabilization (Rahardjo et al. 2013).

This effect is used to confine the wetting front in the upper part of the cover, thus reducing percolation, until a limit capillary

pressure is attained, which allows for the rapid increase of water content into the underlying coarse-grained layer. This value has been called breakthrough suction, but it is not so clearly defined: according to Ross (1990) and Parent and Cabral (2006), it is the matric suction at which the hydraulic conductivity curves of the two soils intersect, while Stormont and Anderson (1999) and Tami et al. (2004) indicated that the breakthrough suction is the water entry value (wev_1 in Fig. 1b) of the coarse-grained soil. Both the interpretations let think that the coarse material has an on-off behavior from an hydraulic point of view. However, as matric potential is continuous across the soil layer interface, infiltration into the coarse soil is a continuum process which only apparently halts. Thus, as it will be better clarified hereinafter, the breakthrough suction should be more correctly defined as the one corresponding to the establishment of a water potential gradient through the interface, large enough to let the infiltrating water pass below significantly. Accordingly, as it was already observed by means of tracer experiments (e.g. Walter et al. 2000), the breakthrough suction depends not only

on the hydraulic characteristics of the soils, but also on the inclination of the interface, on the initial moisture state (which controls the initial suction and hydraulic conductivity at the interface), and on the applied infiltration rate (Damiano et al. 2017).

In inclined covers, under continuous infiltration from the ground surface, during the apparent stop of the wetting front, the moisture that builds up above the interface between the fine and the coarse material leads to the formation of a gravity-driven sub-surface water flow along the sloping interface, which contributes to redistribute part of the infiltrating water downslope. In natural soil deposits the flow along or around these discontinuities is commonly referred to as funneled flow (Kung 1990). Depending on geometrical or boundary variations, at a certain distance downslope, often reported as "diversion length", the degree of saturation of the upper soil layer increases until water starts penetrating significantly into the coarse layer (Ross 1990). The amount of laterally diverted subsurface water flow is strongly dependent on the hydraulic properties of the two materials in contact, in addition to slope

inclination and infiltration rate (Kämpf et al. 2003). In natural slopes, characterized by length in the order of hundreds of meters and irregular layer geometry, the conditions leading to the penetration of infiltrating water into the underlying coarse layer are governed mainly by geometrical and textural heterogeneities.

Although several experimental and mathematical studies have been performed to analyze the response of inclined artificial covers and to identify the most appropriate layer characteristics to increase the efficiency of the capillary barrier covers (Kämpf et al. 2003; Aubertin et al. 2009; Tallon et al. 2011; Zhan et al. 2014), few investigations on the potential formation of capillary or hydraulic barriers in natural shallow unsaturated covers and on their effects on slope stability are available. Many past studies focused on the importance of slope geometry on seepage in natural slopes (Harp et al. 1990; Johnson and Sitar 1990; Bonte et al. 2000), others revealed the main characteristics of infiltration into unsaturated homogeneous slopes under uniform rainfall (Warrick et al. 1997; Lu et al. 2011), many others focused on preferential

flows which mainly govern the infiltration into the most superficial part of the covers (Kung 1990; Walter et al. 2000).

Recently, Hübner et al. (2017), by means of electrical resistivity tomography and pore pressure measurements, were able to observe the formation of both hydraulic and capillary barrier phenomena at two soil layers interfaces and the subsequent development of subsurface water flows, during an artificial rainfall on a 15° inclined natural slope. In this gentle slope, the vanishing of suction and the occurrence of perched water tables was not sufficient to trigger a slope failure. Differently, along steep slopes, characterized by slope angles close to the effective friction angles of the soils in saturated conditions, the increase of the degree of saturation at the interface between two soil layers may lead to instability.

Several attempts of interpretation of the effect of layering on the triggering mechanisms of debris-flows and flowslides have been made, mainly based on 2D seepage analysis, which often led to contrasting results. In the pyroclastic-covered slopes of Campania, some authors looked at the presence of a pumiceous coarse layer in the soil profile as a stabilizing

factor for the slope (Del Prete et al. 1998): the coarser and “highly conductive” pumices were considered as preferential channels, able to drain downslope the infiltrating water, thus impeding the progressive saturation of the lowermost soil. Crosta and Dal Negro (2003) gave a different interpretation, showing that positive pore pressure pulses moving downslope may arise within the “more permeable” layers, which were the first to reach an instability condition. More recently, Mancarella et al. (2012), reinterpreting the triggering mechanism of the Sarno disaster of 1998 (Cascini 2004), argued that a capillary barrier at the upper interface of a layer of pumices could have developed, favoring accumulation and lateral distribution of infiltrating rainfall and a possible diversion of flow towards downslope, thus leading to localized increase in water content and loss of strength. In their evaluation, however, the authors assumed as initial condition at the beginning of rainfall an almost dry moisture profile. This hypothesis deeply affects the hydrological slope response as, depending on the water potential distribution throughout the cover at the onset of rainfall (i.e. on the initial conditions of the soil profile) and on

the rainfall intensity (i.e. the boundary conditions), as it will be better clarified in the following section, the coarse soil layers may affect the infiltration process in very different way. Therefore, it is not obvious that the presence of a coarse layer might induce an accumulation of water above its upper interface, a lateral water redistribution and a localized growth of pore water pressure, worsening the stability condition of a regularly layered shallow slope. To investigate on this aspect, the following sections report the results of physical and mathematical modeling, supported by in situ suction and water content measurements, aimed at addressing the role of the initial conditions in a seasonally fluctuating climatic environment.

3. A case study

A large hilly and densely urbanized area around Naples (south Italy), after prolonged and intense rainfalls, periodically experiences fast slope movements. The covers are the result of wind transportation and air-fall deposition of the pyroclastic materials erupted by the Somma-Vesuvius and Phlegrean

Field volcanic complexes, which gave to the soils a very loose and metastable structure (Picarelli et al. 2006). Along the Apennines, in the distal area from the eruptive centers, the covers, in their primary deposition conditions, are characterized by sequence of layers of pumices overlaid by the ashes originated by the same eruption. The basal formation consists of Mesozoic–Cenozoic fractured limestone. A typical example is the slope near the town of Cervinara, which, after the catastrophic flowslide occurred in December 1999 (Fig. 2a), has been deeply investigated. Along one side of the detachment area of the landslide (Fig. 2b), the soil cover profile is quite regular and continuous and consists of two layers of pumices, few decimeters thick ($0.2\div0.8\text{m}$), embedded between three ashy layers of greater thickness ($0.3\div1.5\text{m}$). The pyroclastic top layer is humified and rich of roots and organic matter. At the bottom of the cover, in contact with the bedrock, a layer of slightly plastic altered ashes is present. The area is subjected to the typical Mediterranean climate, characterized by rainy autumns and winters and hot and dry summers, with a mean annual rainfall height of 1600mm and

maximum rainfall intensities up to about 30mm/h. Yearly maximum daily precipitation is highly variable, ranging from about 30mm to 180mm. The rainstorm which triggered the 1999 flowslide was characterized by a cumulative rainfall height of 320mm fallen in 50 hours with a maximum rainfall intensity of 19mm/h as recorded by the S. Martino Valle Caudina rain gauge located few km far in the downslope area (Damiano et al. 2012).

The flowslide took place on a 40° sloping deposit, covered by chestnut trees. The sliding surface of the 1999 landslide was located at a depth of about 1.5-2.0m (Fiorillo et al. 2001) i.e. at the base of the thickest intermediate ash layer or within the finest pumices which are both cohesionless materials characterized by friction angles in the order of the slope inclination. This suggests that failure may occur only when the soil is very close to saturation. Moreover, the saturation of the soil at failure is one of the predisposing factors for the evolution of these loose granular soils into a flowslide. In fact, even if the intermediate ash layer is susceptible to static liquefaction (Olivares and Picarelli 2003), only when instability

involves the soil in a condition very close to saturation, the establishment of a following undrained or partially undrained response becomes likely, and a post-failure evolution into flowslide may occur.

The occurrence of this post-failure mechanism has been verified by means of physical modelling for the volcanic ashes of Campania (Olivares and Damiano 2007), as well as for other types of loose granular soils (Wang and Sassa 2001). Just after the instability, a sudden increase of pore pressures within the soil occurs, and the rate of displacements assumes values so fast to make reliable the establishment of an undrained post-failure mechanism of static liquefaction, which can be assumed as responsible for the following flow-like style of the sliding soil mass.

Hence, understanding how the presence of layering modifies the suction and the water content distributions within the soil profile is fundamental to correctly predict both the depth of the sliding surface and the post-failure evolution of a rainfall-induced landslide in very loose granular soils.

Hereinafter, the focus will be on the hydrological response of the most superficial part of the soil cover, and in particular on how the presence of the upper pumice layer affects the rainwater infiltration into the intermediate layer of volcanic ash, considered as the one where most frequently the flowslide generation occurs.

3.1 Geotechnical characterization of the pyroclastic cover

A synthesis of the main physical and mechanical characteristics of the soil layers (Olivares and Picarelli 2003; Picarelli et al. 2006; Damiano et al. 2012) is reported in Table 1. Regarding grain size distribution, the soils belong to two main classes: the pumices are essentially gravels with sand, the ashes are silty sands. The porosities of both soils are quite high and the unit soil weights, retrieved by conventional laboratory technique, show a wide range of variation (ashes $25\text{kN/m}^3 < \gamma_s < 27\text{kN/m}^3$; coarse pumices $23\text{kN/m}^3 < \gamma_s < 26\text{kN/m}^3$) due to the internal porosity of the soil particles (Picarelli et al. 2006). With the exception of the altered ashes at the bottom of the soil sequence, all the soils are characterized by a null

effective cohesion and by quite high values of the friction angles in the order of slope inclination ($35^{\circ} \leq \phi' \leq 44^{\circ}$). In unsaturated conditions, the volcanic ashes are characterized by values of the apparent cohesion which increase to about 5-8kPa for a suction of 80kPa (Olivares 2001). It is worth noting that, under the low net stresses which characterize such shallow covers, small values of cohesion are sufficient to ensure the stability of slopes with inclination close to the friction angles of the soils.

The soil water retention curves (SWRC) of the ash belonging to the intermediate soil layer and of the coarse pumices have been retrieved during infiltration tests in homogeneous and layered small scale model slopes reconstituted in a flume (Damiano et al. 2017). Such a procedure allows investigation of the wetting branch of the SWRC near saturation, which is of very difficult determination with other techniques and which is of great interest for the analysis of slope stability during rainfall, especially for slopes characterized by an inclination angle close to the friction angle of the soil, so that instability occurs very close to saturation. Experimental data, reported

in Figure 3b in terms of matric suction ($u_a - u_w$) versus volumetric water content (θ_w), have been fitted through the van Genuchten expression (1980), and the obtained curves indicate that both soils are characterized by an air entry value smaller than 1kPa, and a very steep slope in the transition zone. The water entry value of the ashes is of about 22kPa, whereas that of pumices is of about 9kPa (Fig. 3b). It should also be highlighted that the SWRC are determined during wetting processes, thus no information about the potential presence of hydraulic hysteresis is given. However, as reported by Damiano and Olivares (2010), retention data, from standard laboratory wetting and drying tests on undisturbed specimens of ashes, show that the soil does not exhibit a significant hysteretic behavior.

Saturated hydraulic conductivities (k) range from mean values of about $1 \cdot 10^{-6}$ m/s for the ashes to values at least one order of magnitude higher for the pumices as retrieved by means of permeability tests (Damiano et al. 2012). However for the coarse-textured pumices, which cannot be sampled in undisturbed way, available data refer only to reconstituted

samples. Data from literature (Evangelista et al. 2005) suggest values of the saturated hydraulic conductivity of pumices up to the order of $1 \cdot 10^{-3} \text{m/s}$.

It has to be noted that the main properties of these volcanic soils are quite similar to that found for soils belonging to other investigated sites in the range of 10-20km far from Cervinara (Bilotta et al. 2005; Sorbino and Nicotera 2013).

Regarding the unsaturated hydraulic conductivity, only experimental data on undisturbed ash specimens are available, determined by means of interpretation of the transient phase of suction equalization during suction controlled triaxial tests (the points in Fig. 3c represent an estimation of k with the literature equations indicated in the legend) (Damiano and Olivares 2010), which show that, in the range of suction experienced in the field the hydraulic conductivity of the fine material decreases of about two orders of magnitude (Fig. 3c).

The back analysis of infiltration tests on layered small-scale slopes (Damiano et al. 2017) allowed estimating the hydraulic conductivity functions (HCF) of pumices with the

vanGenuchten-Mualem model. By comparing the HCF of the two granular soils (Fig. 3c), it can be seen that, in unsaturated conditions, pumices mostly exhibit a hydraulic conductivity lower than ashes. Only very close to saturation the hydraulic conductivity of pumices becomes greater than that of ashes, with a saturated value equal to $2 \cdot 10^{-5}$ m/s, which is about one order of magnitude higher than the experimentally retrieved value. Such a difference, quite usual in this kind of analysis, can be ascribed to the different size of the reconstituted soil samples and on the different applied confining effective stress.

3.2. Field monitoring

Field monitoring consisted, in a first period (Fig.4a), in manual suction measurements, collected every 7-10days during years 2002-2007, at different depths within the ash layers, at five tensiometer stations located just aside the detachment area of the flowslide of 1999 (Fig. 2b). A rain gauge provided information about rainfall. Afterwards, during years 2010-2012, the instrumentation was upgraded by installing two stations (Fig.4b), close to each other, for automatic collection of

suction and volumetric water content every two hours, by means of tensiometers equipped with pore pressure transducers and TDR probes connected to a data-logger for acquisition and storage of data.

The depths of installation of tensiometers vary between 0.60m and 2.40m below the ground surface. In detail, the tensiometers were installed in the top-soil at depths ranging between 0.60 m and 0.90 m, in the intermediate ash layer, at depths between 1.30 m and 2.00 m, and in the altered ash layer at the base of the stratigraphical sequence, at depths between 2.20 m and 2.40 m. Details of the adopted equipment and of the installation procedures can be found in Damiano et al. (2012) and Comegna et al. (2016).

The results of the long-term monitoring allowed identifying the cyclic annual response of the cover in terms of matric suction distribution along the soil profile. This, in turn, allowed recognizing the most critical periods with soil moisture conditions that may predispose the slope to landslide triggering.

The long-term low-frequency monitoring showed that (Damiano et al. 2012):

- the cover is subjected to seasonal fluctuations of suction at the various depths. During the dry and hot summer, suction may reach values higher than 60kPa, whereas in winter it rarely exceeds values of 20kPa with minimum values of few kPa;
- in the top part of the cover, suction is affected by single rainfall events, but the corresponding fluctuation amplitude is generally smaller than that occurring over the year;
- in the intermediate and deepest ash layers, matric suction is usually not affected by single rainfall events, and follows only the seasonal trend;
- the amplitude of the fluctuations decreases with depth, with delay increasing with depth.

In order to identify the suction distribution along the soil profile and how it changes during the year, suction measurements have been rearranged as matric suction profiles aggregated seasonally and illustrated in Figure 5. In the same Figure 5, suction profiles retrieved by measurements performed by

Sorbino and Nicotera (2013) and Pirone et al. (2015), respectively at the Sarno and Monteforte Irpino slopes (both few km far from the investigated slope), have been also reported.

It can be noted that the three monitored sites show similar trends during the seasons: the suction profiles are very smooth during winter and early spring, and become more irregular and variable during the following periods. In autumn, the profiles show the progressive wetting of the upper part of the soil cover and the delayed hydrological response of the lower part of the soil deposit to the increasing cumulative precipitations. Thus, values of suction of almost 20-25kPa across the superficial layer of pumices are representative of soil moisture conditions at the beginning of the rainy season in the pyroclastic covers of Campania, which is a crucial period, since it predisposes the covers to the following rainy, and potentially critical, period.

Obviously, by means of this kind of field monitoring, no information was available regarding the moisture condition of the coarse-textured pumices, nor about the behavior of the

layered profile, during or immediately after fast rainwater infiltration. In this respect, the automatic monitoring allowed investigation of the short-term behavior of the cover in response to single rain events, giving particular focus to the role of the initial soil moisture conditions. Moreover, as schematically illustrated in the stratigraphical representation of Figure 4b, in the instrumented station 1 (ST1), the layer of coarse pumices was not present: thus, the role of pumices in a boundary value problem can be analyzed.

Figure 6 illustrates the daily rainfall and the suction and volumetric water content measurements collected from January to May 2011: the red dots represent data collected at station 2 (ST2 - presence of pumices), whereas the black ones are related to station 1 (ST1 - no pumices). Soil suction was measured within the ashes at the same depth of 1.00m in the two stations, while water content was acquired in one case in the pumices, in the other case in the ashes, at about 0.3m of depth. In the monitored period eight main rainfall events occurred, which were characterized by duration ranging between 18 and 110hours, cumulative rainfall heights between

21.8mm and 175.4mm and a maximum hourly rainfall intensity of 12mm/h.

Although suction at the two stations quickly changed in response to rainfall, showing very similar trends, an in-depth observation shows that some differences in the infiltration process exist. An example is reported in the enlargement of Figure 6b, which shows the suction trends after the rainfall event of February 17th as representative of what happened during or just after the major observed rainfall events. It can be noted that:

- below the pumice layer (ST2) a lower suction reduction occurs and, in general, suction values few kPa higher than those recorded at ST1 are observed. This can be clearly noticed during the months of January and February, when the tensiometer at station 2 (red dots in Fig. 6) recorded minimum values of suction between 5-7kPa, while that at station 1 (blue crosses in Fig. 6) recorded minimum values of suction ranging between 2.5-3.5kPa and, in general, the trend of suction during time under the pumice layer (station 2) remained clearly higher than that recorded at station 1;

- the arrival time of the wetting front in depth under the pumice layer (ST2) is slightly anticipated (about 3-4hours) with respect to ST1 (Fig.6b).

This seems to indicate that the top pumice layer, under the field initial and boundary conditions characterized by suctions of about 10kPa and rainfall intensities rarely exceeding 10mm/h, does not hinder the infiltration front advancement, although it causes, in depth, a suction reduction lower than that occurring in a homogeneous soil profile.

Field monitoring also revealed that, during the entire winter season, both soils remained far from saturation, as more than 40% of their total porosity was still available for water storage. Starting from this condition, a potentially triggering rainfall event, in the hypothesis of 1-D infiltration in a 1m thick soil layer, should require a rainfall height of 280mm, corresponding to a rainstorm of 24h with a return period of about 100 years.

Finally, under the investigated initial and boundary conditions, the presence of a layer of pumices seems not to delay the advance of the wetting front, but, by means of increase of water storage, it is able to reduce the amount of water which,

otherwise, infiltrates in depth. However, further investigation are needed as, owing to many other factors affecting infiltration in the field, such as heterogeneity of soil properties, macro-pores, vegetation and so on, no general conclusion can be drawn so far.

3.3 *Physical and mathematical modeling*

In order to investigate the infiltration process in a layered soil profile in simplified and known geometrical and boundary conditions, physical modelling was performed by using an instrumented flume (Olivares et al. 2009). Physical modelling consisted of a series of infiltration tests in three layered small-scale soil deposits, constituted by a coarse pumice layer (4 cm thick) embedded between two ash layers (upper and bottom layer respectively 6 and 10cm thick), having a total thickness of 0.2 m, a width of 0.5 m and lengths higher than 1.5 m. The soils were reconstituted in the flume by moist-tamping technique at porosities in the order of 55-76%, and subjected to rainfall of constant intensity. The effects of the initial moisture conditions, slope inclination, and rainfall

intensity on the process were investigated. The main characteristics of the tests are reported in Table 2 in terms of slope length (L), slope angle (α), rainfall intensity (i) and duration (Δt). Tests indicated as I1-I, I1-IV and I1-V in Table 2 have been already described in Damiano and Olivares (2010) and Damiano et al. (2017).

During the tests, the infiltration process was monitored by means of minitensiometers located at three depths within the ash layers and of a TDR probe (Fig.7a) crossing the entire soil thickness, allowing the retrieval of the volumetric water content profiles along the depth (Greco and Guida 2008). At the bottom and at the base of the slope, a pervious contour was reproduced by means of a geonet covered by a geotextile, characterized by permeability several order of magnitude higher than the investigated soils.

A synthesis of the experimental results is reported in Figures 7b and 7c, which show the arrival times of the wetting front at the depths of the tensiometers under very different applied rainfall intensities (18-105mm/h). The labels near the lines indicate the mean suction values of the soil at the beginning of

rainfall. It looks clear that the pumices slow down the advancement of the wetting front in an initially dry soil profile (Fig. 7b), whereas this effect is not so clear for wetter, but still far from saturation, initial soil profile (Fig. 7c), especially under high applied rainfall intensity. Indeed, looking at the two experiments characterized by similar mean value of suction at the beginning of rainfall (about 25kPa) and by very different rainfall intensity (18mm/h and 83mm/h, respectively in Fig. 7b and c), it can be seen that, although pumices are characterized in both cases by a very similar initial water content, which is higher than their water entry value, the soil profile behaves in a completely different manner. Thus, a not unique value of the breakthrough suction can be assumed, the process being governed not only by the hydraulic properties of pumices but also by the hydraulic gradient which establishes across the interface between the layers.

Nonetheless, a water flow diversion occurs in the upper fine layer when it approaches saturation. This can be inferred from the plot in Figure 8, which shows the trend of the cumulative infiltration in each soil layer and in the whole deposit (bold line

in Fig. 8), as retrieved by water content measurements, compared to the cumulated rainfall height during the test with initial mean suction of 25kPa and rainfall intensity of 18mm/h (Damiano et al. 2017). Initially, the entire rainwater amount is stored in the uppermost layer, which soon reaches and then remains in a nearly saturated condition ($\theta_w < 0.7$). Once the wetting front significantly enters the pumices, water quickly reaches also the lowermost part of the deposit, where it starts being stored. It has to be noted that the cumulative infiltration in the whole deposit gradually diverges from the cumulated rainfall height (Fig.8), indicating that part of the water is drained towards the foot of the slope. As there was no evidence of surface runoff, or of drainage through the base of the flume, it seems that a partial lateral diversion of the water flow establishes. During the last stage of the experiment, all the amount of infiltrating water passes through the pumices without further increase of their degree of saturation: an unsaturated quasi-steady-state condition is reached.

It is important to highlight that under a different boundary condition at the toe of the model slope, the diverted water flow

may lead to a localized accumulation of water and, thus, may induce a local slope failure which progressively may retrogress upslope. Thus, it becomes also important to estimate the amount of the diverted or partially diverted water flow. To this aim, and to support the interpretation of the experimental tests, a mathematical model of 2-D flow through a layered unsaturated porous medium, which integrates the Richards equations by using the finite-difference method, formulated under the hypothesis of rigid soil skeleton, isothermal conditions and neglecting the flux of the gas phase, has been used (Greco et al. 2015). The hydraulic functions of the soils have been modeled with the van Genuchten-Mualem expressions. The boundary condition written at the top soil surface accounts for the formation of surface runoff when the applied rainfall intensity exceeds the maximum infiltration capacity, whereas at the bottom and toe of the flume a seepage face boundary condition has been imposed.

The mathematical analysis of the flow field confirms the main features of the process, indicating that the water flow direction in the uppermost layer, initially orthogonal to the soil surface

due to the high capillarity gradient, first becomes vertical, as soon as the gravitational gradient prevails, then deviates downslope direction through the entire layer: the presence of pumices induces a partial downslope water diversion. In Figure 9, the estimated velocity components parallel to the slope along the middle section of the slope are compared with the downslope component of the vertical infiltration, leading to an estimation of the diverted flow rate of about 2.3% of the total infiltration rate.

Looking at the results of the infiltration test performed with a rainfall intensity of 83mm/h, it can be seen that, in this case, the pumice layer is no more capable of delaying the advancement of the wetting front (Fig.7c). In presence of such a high rain intensity, slightly higher than the estimated saturated hydraulic conductivity of the ashes, the upper soil layer is saturated from the top and, looking at the water stored within the whole deposit (Fig.10), it is clear that, just few minutes after the beginning of rain, not all the effective rainfall is entering the soil deposit, indicating that surface runoff occurs. Although no overland runoff measurements were

available during the test, when the upper layer reaches saturation its amount can be assumed roughly equal to the difference between the effective applied rainfall and the saturated hydraulic conductivity of the ashes, which is not enough to explain the observed difference. Thus, also in this case a sub-surface downslope flow probably occurs. Differently from the previous test, however, the coarse-textured soil layer continues storing water, and by means of both storage and drainage mechanisms the amount of water available for infiltration into the lower layer is reduced. Actually, looking at the volumetric water content profiles illustrated in Figure 11, it seems that, in the final part of the test ($t=80\text{min}$), the upper part of the pumices approach saturation, thus a downslope drainage mechanism might probably arise also through them. However, the small scale of the deposit and the lack of instruments devoted to measure the water flux through the base of the slope did not allow to deeply investigate on this aspect.

4. Effect of layering on stability of pyroclastic covers of Campania

The morphology and the stratigraphy of the shallow pyroclastic deposits of Campania, often characterized by an almost constant slope angle and soil layers parallel to the bedrock, suggest that the infinite slope hypothesis can be assumed to assess the factor of safety (FoS). In unsaturated conditions, the influence of the matric suction on the soil shear strength has to be taken into account in the calculation of FoS. To such aim, shear strength as a function of matric suction can be evaluated by using one of the expressions proposed in the literature (Fredlund et al. 1995; Vanapalli et al. 1996; Khalili and Khabbaz 1998; Alonso et al. 2010; Lu et al. 2010; Greco and Gargano 2015). In the following the expression proposed by Fredlund et al. (1995) has been used.

For the slope of Cervinara, previous stability analyses, performed on the basis of the results of suction monitoring, showed that the minimum values occur at the base of the intermediate ashy layer and never drop under 1.1 even during the wettest winter periods (Damiano et al 2012; Comegna et

al. 2016), indicating that the pyroclastic cover is essentially stable. Nonetheless, starting from a very wet soil profile if a heavy and long-lasting rainfall occurs, a failure condition may be attained.

As described in the previous sections, the presence of a coarse layer of pumices highly affects the suction evolution during infiltration, in turn conditioning the safety factor and the depth of the potential failure surface.

Amount and intensity of rain, as well as the initial soil moisture, are the crucial factors determining different flow paths and suction distribution.

Under low initial moisture and low rainfall (in terms of intensity and/or total height), the coarse layer can effectively delay the advancement of the infiltration front into the underlying liquefiable ashy layer, by means of both water storage and partial lateral diversion of flow. This corresponds to an increase in water content of the upper ashy layer which, depending on the rainfall intensity and history, does not necessary lead to full saturation and, more importantly, to failure. This mechanism likely occurs during dry periods, like

summer and early autumn, when pumices are characterized by mean values of suction higher than 20-25kPa. Thus, the presence of the first layer of pumices may be considered benefic for slope stability, meaning that, at the end of autumn, when the rainy and potentially critical period begins, it is able to reduce wetting of the lowermost part of the cover.

During winter, when the suction profiles are very smooth and characterized by values which drop to only few kPa during the most rainy periods, the role of pumices can be completely different. In situ high-frequency monitoring of the Cervinara slope, as well as physical modeling, showed that, in this case, the first pumice layer does not delay the advance of the wetting front, even though it seems to be capable by a storage mechanism, to reduce the amount of water infiltrating in the lowermost ashy layer.

The evaluation of the effects of layering starting from an extremely wet condition during a potentially triggering rainfall, event, never observed during field monitoring, can be made with the aid of the mathematical model previously calibrated and validated with the infiltration tests performed on the small-

scale artificial slopes. In particular, the 2D infiltration process in a real-size (50m long, 2m thick) three-layered 38° sloping deposit, characterized by uniform initial suction of 4kPa has been simulated. The effect of a rainfall event with an intensity of 10mm/h and a duration of 30 hours ($i=10\text{mm/h}$, $\Delta t=30\text{h}$) which corresponds, in that area, to a rainstorm with a return period of about 100 years (some landslides in the area were triggered by such kind of events), has been analyzed. The slope, as illustrated in Figure 12a, has been schematized using a regular rectangular mesh with elements 0.1m thick and 0.5m long. As boundary conditions a no flow surface has been assumed for the upper edge of the slope, a seepage face boundary condition (i.e. no flow until the matric potential along the face is below the value of -10.0cm, otherwise free outflow) has been imposed at the base surface while at the bottom of the slope a pressure head equal to zero has been assumed. A time step of 300s was adopted.

Due to lack of data, for the top-soil ash layer the same properties of the deeper ashes have been adopted, neglecting any influence on soil hydraulic and mechanical properties

caused by weathering, and by the content of organic matter and roots. The hydraulic properties of the soils adopted in the analysis are those related to the coarse pumices and the volcanic ashes retrieved from physical modeling and described in section 3.1 and in Figure 3 (indicated in Fig. 3 as “Model calibration”).

The results of the analysis are illustrated in Figure 12b and 12c in terms of pore pressure distributions and of velocity vectors in a central part of the slope, respectively 7hours and 16hours after the beginning of rainfall.

The results indicate that, at the arrival time of the wetting front at the upper pumice interface (Fig. 12b), the infiltrating water is not diverted in the upper layer, where a uniform water content establishes, slightly smaller than θ_{sat} . As expected, thanks to the very wet initial conditions pumices do not hinder the infiltration process. However, as the wetting front enters the lowermost ash layer (Fig. 12c), a partial lateral flow diversion occurs again but, in this case, within the intermediate coarse layer. In fact, in these conditions, the lowermost ash layer has an unsaturated hydraulic conductivity smaller than that of

pumices, and the small hydraulic gradient obstacles the progress of infiltration into the bottom layer. This condition continues till the end of the simulated rain. An estimation of the partially diverted water flow rate through pumices indicates that, however, it is a really small percentage (about 0.7%) of the infiltrating water. Thus, in this case, the infiltration front seems to be not significantly influenced by the presence of pumices at the upper interface. Although pumices reach very low values of suction, a full saturated condition is not attained in any of the layers, because the infiltration rate is in any case much smaller than the saturated hydraulic conductivity.

These very different behaviors of the layered cover in turn affect slope stability, which can be analyzed, as already pointed out, under the simplified hypothesis of infinite slope. The mechanical properties of the soils adopted in the analysis are reported in Table 3. For both the top and bottom ash layers, the empirical relationship between apparent cohesion c^* , i.e. the increase of shear strength due to the unsaturated condition of the soil, and suction, experimentally retrieved for the volcanic ashes (Olivares 2001) has been adopted,

whereas no effect of suction on shear strength of pumices has been considered.

The evolution of the FoS at various depths is illustrated in Figure 13, as evaluated in presence (bold lines) and absence of layering (dashed lines). It shows that the minimum FoS are not so different in the two cases, with a slight reduction only at the base of the pumices, where the highest degree of saturation is reached. However, it can be noted that the decrease of the FoS in depth is delayed of some hours by layering. As in an almost uniform soil moisture profile the potential failure surface develops at the base of the profile, this, in turn, means that the potentially triggering rainfall event should be characterized by a longer duration, which, for a given rainfall intensity, corresponds to a higher return period.

Obviously, the proposed results are strongly dependent on the assumptions done about soil properties, especially for those of the top-soil layer, and about slope geometry. It is worth to note that the described positive effect of pumice layers, holds under the infinite slope hypothesis. In fact, in case of more complex slope geometry (e.g. irregular or even discontinuous layers),

the lateral flow diversion may cause local pore pressure increase and reduction of FoS. Depending on specific characteristics of the slope, this local potential instability condition would not necessarily lead to the triggering of a landslide involving a large part of the slope.

5. Conclusions

Rainwater infiltration into unsaturated layered granular deposits is a very complex process and it is still a challenging task for the prediction of the slope behavior. Amount and intensity of rain, as well as the initial soil moisture condition at the beginning of rainwater infiltration, are the crucial factors determining partial diversion of the water flow and different suction distribution along the soil profile, in turn related to different FoS of the slope.

To investigate on this topic, the results of physical and numerical modeling of infiltration in three-layered small-scale slopes and the analysis of field monitoring along a slope subjected to a catastrophic flowslide in 1999, have been analyzed. The study reveals that, along the shallow steep air-

fall pyroclastic covers of Campania, characterized by quite regular alternating layers of ashes and pumices, under humid climate typical of Mediterranean area, two main different effects of layering can arise.

During rainstorms occurring at the beginning of rainy season, when the soil profile is still quite dry and characterized by suction values of about 20-25kPa, the presence of a coarse-textured soil layer under the top-soil prevents the deepening of all the infiltrating water into the lower liquefiable ashes, resulting in a water storage in the upper layer up to, eventually, the establishment of partial diversion of water flow. Thus, the presence of a first layer of pumices may be considered benefic for slope stability, meaning that, at the end of autumn, when the rainy and potentially critical period begins, it is able to reduce wetting of the lowermost part of the cover.

Differently, during winter and early spring, when the suction profiles are very smooth, the role of pumices can be completely different. In this case, as revealed by both physical modeling and field monitoring, the first pumice layer is not

effective in delaying the advance of the wetting front, even though it seems to be capable, by means of a storage mechanism, to reduce the amount of water infiltrating into the lowermost ash layer. Actually, a mathematical investigation of a potentially triggering rainfall-event reveals that a partial lateral flow diversion may occur again but, in this case, within the pumice layer. In this very wet condition, the progress of the infiltration towards the bottom of the stratigraphical sequence is hindered by the presence of finer layer below the coarser one. Under the simplified hypothesis of infinite slope, this corresponds to a slight reduction of the FoS at the base of the first pumice layer but, also, to a delay of some hours of the decrease of the FoS in depth. This, in turn, means that, as the minimum FoS, in a uniform soil profile, localizes at the base of the cover, the potentially triggering rainfall event should be characterized by a longer duration, which, for a given rainfall intensity, corresponds to a higher return period. In soil covers presenting another coarser layer at a greater depth, soil rupture may likely occur at the interface between the pumices and the lowermost ashy layer, where the highest degree of

saturation is expected and other stabilizing factors such as pedogenized soils, roots reinforcement and water uptake, typically acting in top soils, are scarcely effective.

Obviously, these simplistic considerations hold for idealized regular and continuous layered soil covers. Along real slopes, characterized by complex morphologies, lateral redistribution of water (3D effects), lacks in layers continuity and other minor effects may induce flow concentration, locally leading to failure.

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Figure Captions

Figure 1. Schematic hydraulic conductivity functions (a) and water retention curves (b) for coarse and fine soils

Figure 2. a) Photo of the December 1999 flowslide; b) schematic section (A-A') of the slope, stratigraphy and location of the instrumented verticals

Figure 3. a) Grain size distribution of the investigated soils; b) Soil water retention curves and; c) Hydraulic conductivity functions

Figure 4. a) Instrumented stations for long-term manual monitoring of suction (2002-2008); b) stations for automatic collection of volumetric water content and matric suction (2010-2012)

Figure 5. Suction profiles collected at Cervinara slope compared with those collected at Pizzo d'Alvano and Monteforte Irpino: a) from January to April; b) from May to August; c) from September to December

Figure 6. Daily rainfall and the suction and volumetric water content measurements collected during: a) winter and spring 2011; b) the rainstorm event of 16th February

Figure 7. a) View of the reconstituted layered profile with the location of the sensors; b) and c) arrival times of the wetting front at various depths during the infiltration tests

Figure 8. Cumulative water storage in the layered deposit under a rainfall intensity of 18mm/h

Figure 9. Values of the velocity component parallel to the slope along the middle section of the slope

Figure 10. Cumulative water storage in the layered deposit under a rainfall intensity of 83mm/h

Figure 11. Volumetric water content profiles during infiltration under constant rainfall intensity of 83mm/h

Figure 12. Mathematical modeling of infiltration into a layered real-size slope: adopted mesh and assumed boundary conditions (a); pore pressure distributions and velocity vectors 7hours (b) and 16hours (c) after the beginning of rainfall.

Figure 13. Evolution of the FoS at various depths for an homogeneous and a layered soil profile.

Table 1. Main physical and mechanical characteristics of the pyroclastic soil layers of Cervinara slope.

Layer	γ_s (kN/m ³)	γ_d (kN/m ³)	n (%)	S_r (%)	c' (kPa)	ϕ' (°)	k_{sat} (m/s)
Coarse pumices	25	13	70	32	0	40-44 ⁺	$5 \cdot 10^{-6}$
Ashes	26	14	72	80	0	38	$1 \cdot 10^{-6}$
Fine pumices	26	14	67	36	0	38-42 ⁺	$8 \cdot 10^{-7}$
Altered ashes	26	16	60	75	4	35	$5 \cdot 10^{-7}$

+ data from literature

Table 2. Characteristics of the experimental tests on small-scale layered deposits.

Test	L (m)	α	$(u_a - u_w)_0$ (kPa)	i (mm/h)	Δt
I1-I	1.74	0°	60	45	1h 01min
I1-II	1.74	0°	34	27	2h 32min
I1-III	1.74	20°	4	27	0h 21min
I1-IV	1.74	38°	25	18	4h 50min
I1-V	1.74	38°	23	83	1h 55min
I1-VI	1.74	38°	10	105	7h 25min
I2-III	1.65	20°	38	18	1h 00min
I2-IV	1.65	20°	14	36	1h 00min
I2-V	1.65	38°	27	46	3h 20min

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Table 3. Adopted properties of the soils used for stability analysis evaluation.

Layer	γ_s (kN/m ³)	c' (kPa)	c^* (kPa)	ϕ' (°)
Top-soil	26	0	$2.38\ln(u_a - u_w)$	38
Coarse pumices	25	0	0	44
Ashes	26	0	$2.38\ln(u_a - u_w)$	38

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Figures

Figure 1. Schematic hydraulic conductivity functions (a) and water retention curves (b) for coarse and fine soils

Figure 2. a) Photo of the December 1999 flowslide; b) schematic section (A-A') of the slope, stratigraphy and location of the instrumented verticals

Figure 3. a) Grain size distribution of the investigated soils; b) Soil water retention curves and; c) Hydraulic conductivity functions

Figure 4. a) Instrumented stations for long-term manual monitoring of suction (2002-2008); b) stations for automatic collection of volumetric water content and matric suction (2010-2012)

Figure 5. Suction profiles collected at Cervinara slope compared with those collected at Pizzo d'Alvano and Monteforte Irpino: a) from January to April; b) from May to August; c) from September to December

Figure 6. Daily rainfall and the suction and volumetric water content measurements collected during: a) winter and spring 2011; b) the rainstorm event of 16th February

Figure 7. a) View of the reconstituted layered profile with the location of the sensors; b) and c) arrival times of the wetting front at various depths during the infiltration tests

Figure 8. Cumulative water storage in the layered deposit under a rainfall intensity of 18mm/h

Figure 9. Values of the velocity component parallel to the slope along the middle section of the slope

Figure 10. Cumulative water storage in the layered deposit under a rainfall intensity of 83mm/h

Figure 11. Volumetric water content profiles during infiltration under constant rainfall intensity of 83mm/h

Figure 12. Mathematical modeling of infiltration into a layered real-size slope: adopted mesh and assumed boundary conditions (a); pore pressure distributions and velocity vectors 7 hours (b) and 16 hours (c) after the beginning of rainfall.

Figure 13. Evolution of the FoS at various depths for an homogeneous and a layered soil profile.