DOI: 10.4408/IJEGE.2021-01.S-20

LANDSLIDE SUSCEPTIBILITY ASSESSMENT IN PYROCLASTIC SOILS: NUMERICAL ANALYSIS ON THE ROLE OF CAPILLARY BARRIERS

Ciro SEPE[*,**], Domenico CALCATERRA[**], Diego DI MARTIRE[**], Massimo RAMONDINI[***], Giacomo RUSSO[**], Enza VITALE[**] & Lucia PAPPALARDO[****]

[*] University of Cassino and Southern Lazio - Department of Civil and Mechanical Engineering - 03043 Cassino (FR, Italy)
[**] Federico II University of Naples - Department of Earth Sciences, Environment and Resources Sciences - 80126 Naples (Italy)
[***] Federico II University of Naples - Department of Civil, Architectural and Environmental Engineering - Via Claudio, 21 - 80125 Naples (Italy)
[****] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli, Osservatorio Vesuviano - Via Diocleziano, 328 - 80124 Naples (Italy)
Corresponding author: ciro.sepe@unina.it

EXTENDED ABSTRACT

Il lavoro riguarda lo studio dei fattori di innesco di fenomeni franosi a cinematica rapida che coinvolgono le coltri piroclastiche di alcuni contesti geologici della Campania. Tali depositi sono essenzialmente da fall out e di origine prevalentemente vesuviana; spesso in giacitura primaria, sono riferibili in particolare alle eruzioni avvenute circa 22.000 anni fa (*Pomici di Base*), 8.900 anni fa (*Pomici di Ottaviano*) e 4.365 anni fa (*Pomici di Avellino*) e secondariamente alle eruzioni subpliniane del 472 d.C. (*Pollena*) e del 1631, separate in genere da paleosuoli spessi alcuni decimetri.

In particolare l'area di studio, posta ai margini orientali della Piana Campana, ha interessato i versanti del territorio comunale di Palma Campania, parte della più ampia dorsale carbonatica dei Monti di Sarno. Durante il rilevamento geologico sono state cartografate delle frane, relativamente recenti, con movimento iniziale del tipo scorrimento traslativo, la cui osservazione ha permesso di comprendere che una delle cause in grado di determinare la rottura iniziale è dovuta alla possibile formazione di barriere capillari durante eventi di pioggia, favorita dalla significativa variazione di porosità e di permeabilità fra livelli di pomici grigie e scorie nere. Tale variabilità è stata pertanto indagata nel dettaglio, alla scala della microstruttura e del laboratorio. I depositi piroclastici interessati sono depositi da fallout in giacitura primaria a diversa granulometria e grado di vescicolazione, che si possono attribuire all'eruzione vesuviana delle cosiddette Pomici di Base datata circa 22 ka. Sono stati prelevati campioni a diverse altezze nella successione stratigrafica per sottoporli ad analisi per la determinazione delle caratteristiche fisiche (granulometria, peso specifico e densità) e caratteristiche tessiturali mediante microtomografia a raggi X, la quale ha consentito di determinare su campioni ricostituiti sia porosità sia conducibilità idraulica. Le analisi sperimentali hanno evidenziato quindi una variabilità lungo la successione piroclastica esaminata di granulometria, peso specifico e densità dei materiali. I risultati ottenuti hanno supportato l'ipotesi di possibile formazione di barriere capillari al passaggio fra pomici grigie e scorie nere nel corso dei fenomeni di infiltrazione; tale ipotesi è congruente con l'osservazione della posizione delle superfici di rottura delle frane osservate in campagna.

L'ipotesi è stata sottoposta a verifica mediante simulazioni numeriche che hanno consentito di ricostruire il processo d'infiltrazione dell'acqua meteorica ed il relativo avanzamento del fronte umido nei livelli stratigrafici al variare delle caratteristiche tessiturali (granulometria, porosità, conducibilità idraulica). Per le simulazioni numeriche è stato considerato un modello alla meso-scala (2D), utilizzando il software VS2DTI open source alle differenze finite sviluppato dall'U.S.G.S. per la simulazione di processi di infiltrazione nei terreni parzialmente saturi. In particolare, nel caso di simulazioni con piogge di lunga durata e bassa intensità (5mm/h), con terreni inizialmente caratterizzati da ridotti valori del contenuto d'acqua volumetrico, si è osservata una lunga permanenza della barriera capillare (oltre 48 h), che favorisce l'accumulo di acqua negli strati più superficiali fino al raggiungimento di un elevato grado di saturazione (circa 85%) con conseguente diminuzione del livello di suzione, e con la conseguente variazione della resistenza al taglio del materiale. In occasione di eventi di pioggia più intensi, a parità di condizioni iniziali della coltre piroclastica, si è osservata la formazione della barriera capillare caratterizzata tuttavia da una permanenza limitata, e conseguentemente un valore di grado di saturazione della coltre superficiale relativamente inferiore. Tale aspetto evidenzia come questo fenomeno sia rilevante nel determinare le caratteristiche di stabilità della coltre superficiale, legate alla resistenza al taglio in condizioni di parziale saturazione.

Lo studio evidenzia l'importanza della caratterizzazione di dettaglio dei diversi livelli piroclastici coinvolti nella stabilità dei pendii attraverso un approccio multidisciplinare. I risultati infatti mostrano come le discontinuità tessiturali possano influenzare i fenomeni di infiltrazione e di conseguenza la stabilità delle coltri. L'approccio multidisciplinare, consentendo di aggiungere importanti informazioni per la caratterizzazione fisica dei materiali studiati, contribuisce all'affidabilità e alla robustezza dei modelli di suscettibilità a franare delle coltri piroclastiche.

ABSTRACT

Landslides in pyroclastic soils are among the most calamitous natural phenomena causing damage to people and territory every year. The mechanisms underpinning such landslides can be controlled by multiple factors, including site conditions and features of pyroclastic soils. Spatial variations of textural characteristics and related hydro-mechanical features in the overlain pyroclastic layers can yield to relevant effects on water infiltration, with potential formation of capillary barriers at the interface between different soil layers.

A better knowledge of the key triggering factors, based on engineering-geological modeling, may be carried out through a detailed field and laboratory measurements, as well as performing numerical simulations. The area surrounding Palma Campania (Napoli, Italy) is largely affected by fast-moving landslides involving pyroclastic deposits. The volcanoclastic sequence is constituted upward by (white and grey) vesicular pumices and (black) dense scoriae levels, associated with the Somma-Vesuvius "Pomici di Base" Plinian eruption (22 ka). Stratigraphic sections along the carbonate slopes of Vallone Lupici reveal failure surfaces along various pyroclastic contact layers (white/gray vesicular pumice and dark dense scoria layers).

Representative samples were collected at different stratigraphic heights and analyzed to define structural and textural characteristics; the obtained data were used as input parameters to perform 2D numerical simulations to explore the propagation of hydraulic front under different conditions of water flow (flow rate) and textural features of rocks. The obtained results allow us to put constrains on capillary barriers development in function of soils characteristic and rain fall intensity.

Keywords: *pyroclastic soils, capillary barrier, numerical analysis, landslide susceptibility*

INTRODUCTION

Landslides are among the most hazardous natural phenomena causing worldwide damage to people and territory every year. In Campania region (Italy), slope instability represents a problem of great social impact, for both number of victims and damage caused to buildings, industries and infrastructures. Specifically, the instability of the pyroclastic deposits covering the Campanian carbonate slopes of the peri-Vesuvian area (Monti di Avella, Sarno and Lattari) represents one of the major factors of risk as it generates rapid and long runout landslides, that were responsible for great loss of properties and human lives. Thus in the last decades, particularly following the high impact caused by the tragic events of Sarno (5 and 6 May 1998 - 160 victims), it has received increasing attention in the scientific community and government officials (Calcaterra *et alii*, 2003, 2004; Di Martire *et alii*, 2012), with the aim to proper define the extent of the areas potentially affected by further landslides, and to establish a critical value of rainfall for the temporary evacuation of the population.

To achieve these goals, however, it is crucial to better identify key factors triggering failure initiation and propagation, as they influence both the invasion areas, as well as the rainfall threshold. Recent researches suggested that detachment mechanisms of these rain-induced landslides can be controlled by different factors; nevertheless, a main feature has been assumed in the peculiar textural properties of the layered pyroclastic soils (e.g. De Vita *et alii*, 2013; Cascini *et alii*, 2014; Urciuoli *et alii*, 2016; Damiano *et alii*, 2017). Abrupt variations of textural characteristics (grain size, porosity, permeability, etc.) among the pyroclastic levels can in fact determine a different water infiltration behavior and thus the development of capillary barriers (e.g. Shackelford *et alii*, 1994; Khire *et alii*, 2000, Scarfone, 2020). Such phenomena, related to the capillary tension, limit the downward movement of the wetting front from a finer soil into underlying coarser soils, thus leading to a localized increase in the water content and loss of strength.

These processes have been tested through laboratory experiments in pyroclastic soils only at the macro-scale (e.g. Mancarella *et alii*, 2012a, 2012b); thus, the complex relationships between the intensity/duration of rainfall and micro-textural features of the deposits in controlling the development and protracted actions of capillary barriers remain unclear. A major source of uncertainty is represented by the lack of quantitative textural and geotechnical data, particularly at the micro-scale, directly measured on pyroclastic deposits. Many modelling studies devoted to volcanic hazard assessment, in fact, rely only on the generic use of available published data, often related to generic volcanic materials and conditions, instead of the natural soils involved in the phenomena.

The case study the Vallone Lupici (Palma Campania), located in the Sarno Mts. ridge (Campania, Italy) has been recently studied by Sepe (2019). A detailed field investigation has evidenced a series of confined landslides involving pyroclastic deposits of Vesuvian origin. Particularly, field observations have evidenced the occurrence of failure surfaces in correspondence of marked grain size and textural discontinuities. Consequently, to explore at the micro-scale the conditions possibly favoring the development of efficient capillary barriers, samples of pyroclastic soil at different stratigraphic depths were collected, in particular at the interface of the failure surface. Measurements of micro-textural characteristics via X-ray computed microtomography on semi-undisturbed whole samples, as well as individual pyroclastic grains were performed.

In the paper the hypothesis of capillary barrier formation as relevant triggering factor of rapid landslides is considered.

Water infiltration simulations by finite-differences 2D numerical model have carried out with reference to highly reliable measured textural parameters of pyroclastic layers as input data. Characteristic rainfall events have been considered as hydrological input of numerical calculations. The obtained results highlighted the formation and persistence of capillary barriers at the interface between finer layer and coarser layer in the pyroclastic succession of Vallone Lupici. The study will contribute to the understanding of the key factors controlling the detachment of rapid and long runout landslides and finally to their susceptibility assessment.

WORKING PRINCIPLE OF CAPILLARY BARRIERS

The working principle of capillary barriers is based on the unsaturated properties of stratified layers. Differences between hydraulic properties (i.e., water retention, hydraulic conductivity) of two soil layers of different grain size distributions, namely an upper finer-grained layer overlying a coarser-grained layer, can promote the formation of capillary barriers during an infiltration event. In saturated conditions, the hydraulic conductivity of the coarser layer is higher than that of the finer layer, whereas in unsaturated conditions the situation can be the opposite. In Figure 1 water retention curves and hydraulic conductivity functions of fine grained and coarse grained soils have been compared. For a generic suction value A, the coarser layer is characterized by lower hydraulic conductivity than the finer layer ($k_{c,u}(A)<k_{f,u}(A)$ in Fig. 1b), being the coarser layer at lower degree of saturation because of differences in the water retention behaviour ($S_{r,c}(A)<S_{r,u}(A)$ in Fig 1a). During an infiltration event, the coarser layer acts as low permeability barrier as long as it remains at low degree of saturation. The infiltrating water is stored in the finer layer as a consequence of capillary barrier effect. Increasing the amount of water stored in the finer layer (i.e. sustained heavy rainfall), near the interface between the two layers suction decreases. Equilibrium of the liquid phase implies that matric suction is continuous across the interface between the two layers. Thus, as suction decreases at the bottom of the finer layer, it also decreases at the top of the coarser layer, increasing its hydraulic conductivity. Breakthrough of the capillary barrier occurs, and water starts flowing from the finer layer to the coarser layer. Bulk water forms a continuous liquid network in the coarser layer and water flow starts downward (Stormont *et alii* 1999).

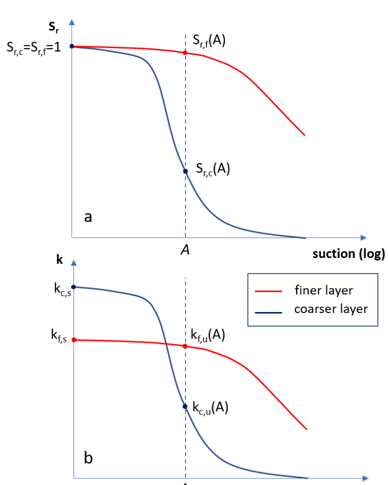

Fig. 1 - Conditions predisposing the formation of capillary barriers: a) water retention curves of upper fine layer and lower coarse layer; b) hydraulic conductivity function of water retention curves of upper fine layer and lower coarse layer

MATERIALS

Stratigraphy and representative sampling

The case study includes the municipal territory of Palma Campania which is located in the "Conca Napoletana (Neapolitan basin)" at the border of Nola and Sarno plains, delimited to the East by the Appennine Mesozoic limestone reliefs and to the West by the Somma-Vesuvius Quaternary volcanic complex (Fig. 3). A detailed field study allowed us to identify a series of recent confined landslides, mainly located in the "Vallone Lupici", involving the Somma-Vesuvius pyroclastic deposits (Fig. 2). They generally include few meters

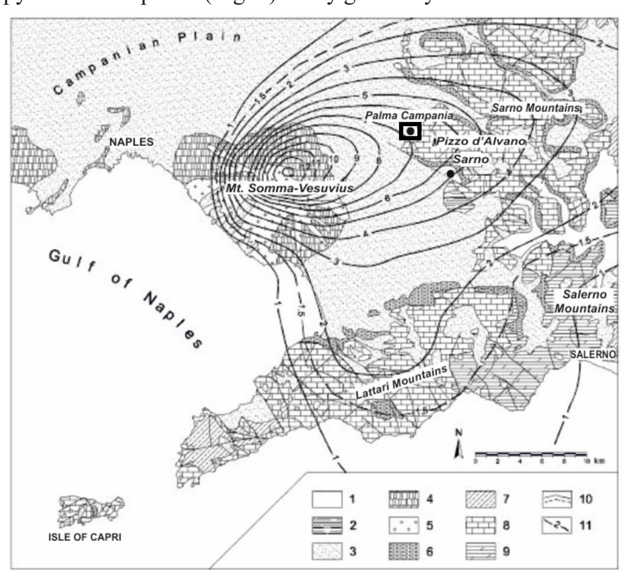

Fig. 2 - Geological map of the south-western portion of the Campanian plain. 1) Alluvial deposits; 2) Travertine; 3) Loose ash-fall deposits; 4) Mainly coherent ash-flow deposits; 5) Lavas; 6) Debris and slope talus deposits; 7) Miocene flysch: 8) Middle Jurassic-Upper Cretaceous limestones; 9) Lower Triassic–Middle Jurassic dolomites and calcareous limestones; 10) Fault; 11) Total isopach lines (m) of the most important Mt. Somma-Vesuvius explosive eruptions. Modified from De Vita et alii (2006)

thick fallout deposit consisting, from the base to the top (Fig. 3), of a basal high-vesiculated white pumice layer, an intermediate level of high to moderate vesiculated gray pumices and an upper level of denser dark scoriae; this stratigraphic sequence (Fig. 4) corresponds to fallout deposits emplaced during the so called "Pomici di Base" Plinian eruption (22 ka, Santacroce *et alii*, 2008) of Somma-Vesuvius volcano, well described in the literature (e.g. Bertagnini *et alii* 1998; Landi *et alii* 1999; Pappalardo *et alii*, 2018; Buono *et alii*, 2020 a and b).

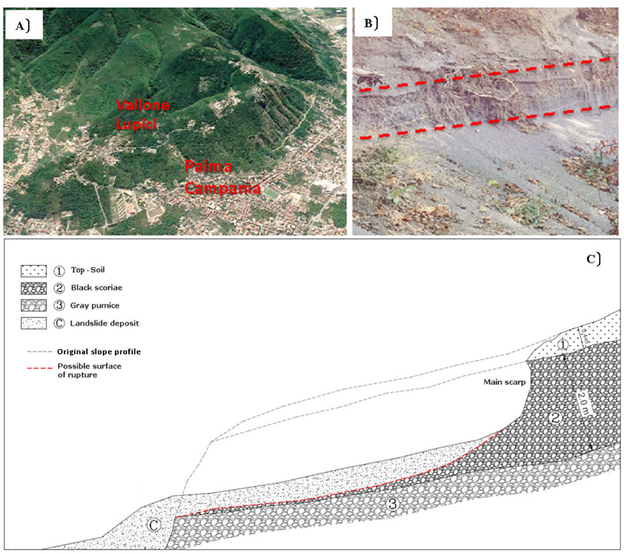

Fig. 3 - A): 3D satellite image of the studied area (from Google Earth); B) Detachment zone of the landslide (Vallone Lupici); C) Cross-section of a typical landslide

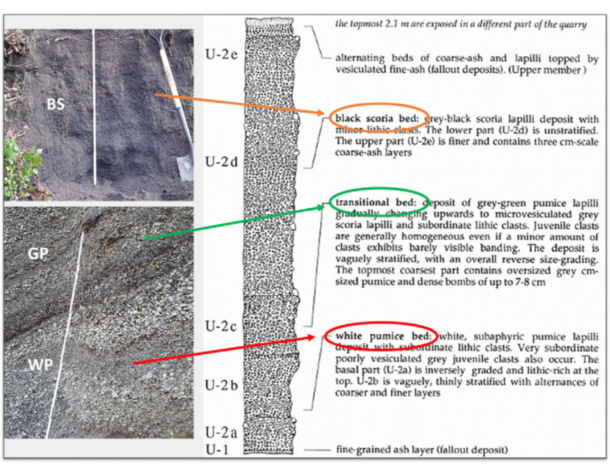

Fig. 4 - Vallone Lupici pyroclastic deposits: identification of Pomici di Base Plinian Eruption layers (BS: black scoriae, GP: grey pumices, WP: withe pumices) and comparison with stratigraphic sequence proposed by Bertagnini et alii (1988)

Representative samples of coarse grained pumices were collected at different heights along the stratigraphic sequence by using thin-walled tube samplers (Fig. 5). The collected samples were analyzed for the measurement of: 1) grain size distribution by sieving and specific gravity by water pycnometry; 2) density of single clasts by water pycnometry; 3) microscopic quantification of both isolated and interconnected porosity on reconstituted samples, as well as on single clasts, through XRay computed microtomography (µXRCT). The obtained key textural parameters were used as input data for hydraulic conductivity and water infiltration numerical simulations described in the following.

Fig. 5 - Vallone Lupici. Sampling of fallout deposit of Pomici di Base Plinian eruption (22 ka)

Physical properties

Grain size distribution of pyroclastic samples vary along the stratigraphic sequence. As reported in Fig. 6, according to ASTM D422 black scoriae are formed by 80% sand and 20% gravel, gray pumices by 80% gravel and 20% sand, and white pumices by 70% gravel and 30% sand.

Density of solid phase varies between 27.2-28.2 kN/m^3 for black scoriae, whereas is between 25.9-27.3 kN/m^3 for gray pumices, and between 23.5-24.2 kN/m^3 for white pumices. Variations of solid density are in agreement with geochemical changes described in literature (Bertagnini *et alii*, 1998), from dense trachybasaltic-latitic scoriae of top layer to light trachytic pumices at the bottom of volcanic succession.

Bulk density measurements, carried out on at least n.100 single clasts of each representative class (namely 2 mm, 5 mm and 10 mm), showed no significant variations within each stratigraphic unit (Fig. 7). Bulk density increases from the base to the top of stratigraphic succession, with lower modal values pertaining to basal withe pumices (modal value 5.9 kN/m^3, range 2.0-9.8 kN/m^3), intermediate values to grey pumices (modal value 10.8 kN/m^3, range 6.9–21.6 kN/m^3) and higher values to black scoriae (modal value 14.7 kN/m^3, range 8.8–23.5 kN/m^3).

As reported in Sepe (2019), total porosity of the layers,

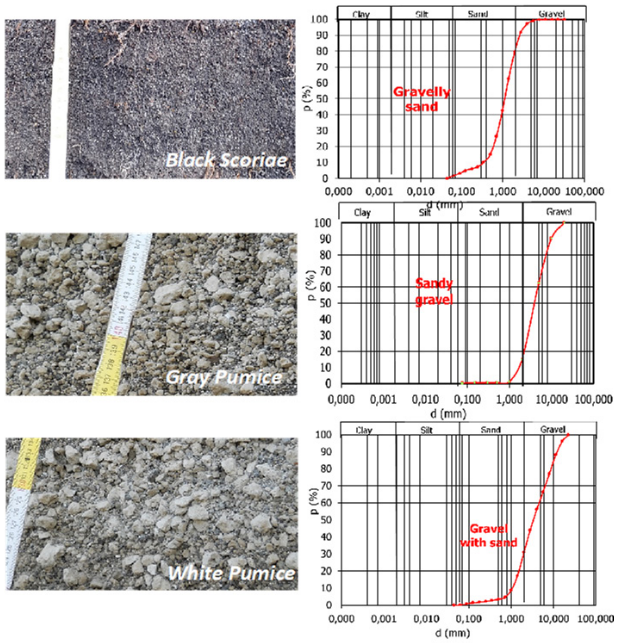

Fig. 6 - Grain size distribution of the analyzed layers in stratigraphic succession

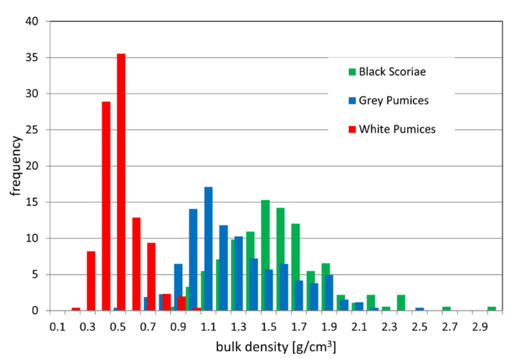

Fig. 7 - Bulk density values of the analyzed samples in stratigraphic succession

evaluated from micro–Xray computed tomography results on reconstituted samples, varied from the 43% in the basal layer of white pumices to 36.5% in the grey pumices layer, down to 33.8% for black scoriae layer. The hydraulic conductivity associated to intergranular pore space was equal to $k=8.9*10^{-2}$ m/s for gray pumices and $k=5.4*10^{-3}$ m/s for black scoriae.

WATER INFILTRATION SIMULATIONS

To test the hypothesis of capillary barrier formation at the interface between black scoriae and gray pumices, a numerical simulation of water infiltration process has been carried out by using VS2DTI finite-difference numerical code (Lappala *et alii*, 1987) for solving problems of variably saturated, single-phase flow in porous media.

The stratigraphic sequence in the numerical model has been reproduced as showed in Fig. 8. Input parameters have been derived from experimental data on the collected samples. Porosity and saturated hydraulic conductivity of each layer were derived by µXRCT data, as described in the previous section. The intragranular porosity of pyroclastic deposits has not been considered in the analyses. Volumetric water content has been considered with reference to dry and wet conditions, in order to verify its influence on capillary barrier formation. The water retention properties of each layer have been implemented with reference to Van Genuchten model, assuming as model parameters data suggested by Mancarella *et alii* (2012), De Vita *et alii* (2013), Pirone *et alii* (2014), Damiano *et alii* (2017) for similar pyroclastic formations of the same region.

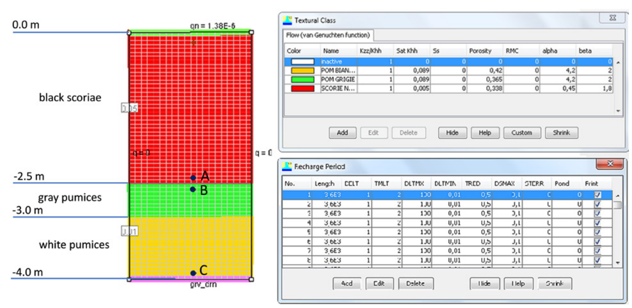

Fig. 8 - The numerical column infiltration model (on the left) reconstructed on the basis of the studied representative stratigraphic succession: 1) basal white pumice layer with a subordinate content in lithics, for a thickness of 1 m (in yellow); 2) intermediate level of gray pumice and scoriae, for a thickness of 0.5 m (in green); 3) upper level of black scoriae and subordinate lithic clasts, for a thickness of 2.5 m (in red). Input simulation parameters are shown on the right tables (please see text for further explanations). A, B and C are the observation points

The initial parameters considered in the numerical model have been summarized in Tab. 1.

layer	initial volumetric water content θ		porosity n	saturated hydraulic conductivity k_s (m/s)	residual volumetric water content	α (1/m)	β
	dry	*wet*					
black scoriae	0.05	0.18	0.338	0.005	0	0.45	1.8
grey pumices	0.01	0.06	0.365	0.089	0	4.2	2
white pumices	0.01	0.06	0.420	0.089	0	4.2	2

Tab. 1 - Numerical model: initial values of the relevant parameters

Observation points were considered in the model for analyzing time series of relevant variables (suction, water content, flow velocity, etc.). Observation points (showed in Fig. 8) were located immediately above (point A) and below (point B) the interface between the upper finer layer and intermediate coarser layer, where capillary barrier is supposed to form, as well as at the bottom of the model (point C).

No flux has been allowed through the vertical boundaries of the model, whereas gravity drainage of the bottom side has been set. A 48h and 192h duration of infiltration process has been considered, with low-intensity (5 mm/h) and intense (50 mm/h) rainfall events.

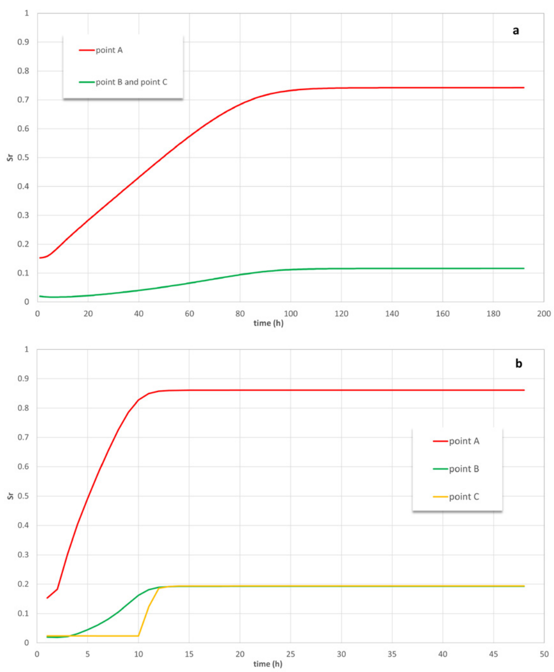

Fig. 9 - Numerical model results: dry initial volumetric water content, a) 192h duration, low intensity (5 mm/h) rainfall event; b) 48h duration, intense (50 mm/h) rainfall event

The formation and persistence of a capillary barrier at the interface between the finer layer of black scoriae and the coarser gray pumice layer was evidenced from the numerical results. As showed in Fig. 9a, with reference to dry initial volumetric water content (θ between 1% and 5%), for long lasting (192 h) and low intensity (5 mm/h) rainfall events, the results show the formation and persistence of capillary barrier for 30 hours. After the breakthrough, the stationary condition is attained after 110 h with degree of saturation of the finer layer Sr = 0.72 and of the coarser layer Sr = 0.11. For intense rainfall event (50 mm/h), the capillary barrier remains active for a short period (3 h), until suction at the interface reaches the critical breaking value, as showed in Figure 9b. The stationary condition is attained when degree of saturation of the upper layer become relatively high (Sr = 0.85), while the degree of saturation of coarser layer is Sr = 0.19. For the lower intensity rainfall events (e.g. 0.6 mm/h), the formation of capillary barrier is evidenced over the entire time interval considered (240h), as confirmed by constant degree of saturations of each layer underlying the interface (Fig. 10). No capillary barrier formation has been observed for the considered higher water contents reported in Tab. 1.

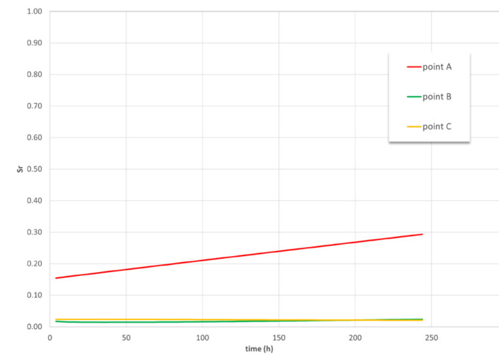

Fig. 10 - Numerical model results: dry initial volumetric water content, long term duration, low intensity (0.6 mm/h) rainfall event

CONCLUSIONS

Investigations on landslides observed in the studied area (Sarno Mountains in Campanian region, Italy) support the hypothesis that porosity and permeability variations at the interface between different pyroclastic levels can be a main detachment factor of surface failure and propagation, due to the saturation induced during a rainfall event induced by the formation of capillary barriers.

The investigated deposit is a succession of fallout layers of different grainsize and degree of vesiculation, attributed to the so-called "Pomici di Base" Vesuvius plinian eruption dated about 22 ka (Santacroce *et alii*, 2008). In detail it is constituted from bottom to the top by a level of white pumice, a transition level of gray pumice, an upper level of dark scoriae (Bertagnini *et alii* 1998; Landi *et alii* 1999).

Detailed micro-textural analyses evidence a marked variation in the textural, geotechnical and hydraulic characteristics among different pyroclastic layers according to the stratigraphic position, in particular at the interface between black scoriae and grey pumice layers, where landslides failure surfaces are observed in the field. This finding support the hypothesis of development of capillary barriers at this interface during rainfall events, causing progressive saturation of the upper layer and subsequent loss of stability. To test this hypothesis, water infiltration process in the pyroclastic layers sequence has been simulated through a numerical model, selecting as input parameters textural and hydraulic characteristics measured on the collected samples.

The results allow to draw the following conclusions:

- due to differences in textural and geotechnical features, capillary barrier forms at the interface of the black scoriae and grey pumices layer if their initial volumetric water content is reduced (dry condition);
- in dry initial conditions, the persistence of capillary barrier depends on the intensity of the rainfall event (short persistence for intense rain and vice versa);

- the persistence of capillary barrier regulates the final saturation degree of the upper and lower layers, influencing in turn their mechanical behaviour and slope stability in general.

The study highlights the importance of detailed characterization of different pyroclastic levels involved in slope stability through a multidisciplinary approach. The results show the role of textural and structural discontinuities between different pumice levels, evidencing the limits of considering the pumice levels as a homogeneous formation from geotechnical point of view.

This kind of multidisciplinary studies will contribute to hazard assessment based on different geology-based parameters (including textural features of pyroclastic levels), thus adding advanced and complete information to the susceptibility models increasing in turn their reliability and robustness.

REFERENCES

Bertagnini A., Landi P., Rosi M., Vigliargio, A. (1998) - *The Pomici di Base plinian eruption of Somma-Vesuvius*. Journal of Volcanology and Geothermal Research, **83** (3-4): 219-239.

Buono G., Pappalardo L. & Petrosino P. (2020a) - *Magma storage and ascent during the largest eruption of Somma-Vesuvius volcano: Pomici di Base (22 ka) Plinian event*. Bollettino di Geofisica Teorica ed Applicata Vol. **61**.

Buono G., Pappalardo L., Harris C., Edwards B.R. & Petrosino P. (2020b) - *Magmatic stoping during the caldera-forming Pomici di Base eruption (Somma-Vesuvius, Italy) as a fuel of eruption explosivity*. Lithos, 370–371.

Calcaterra D., De Riso R. & Santo A. (2003) - *Landslide hazard and risk mapping: experiences from Campania, Italy*. Proc. Intern. Conf. On Fast Slope Movements: Prediction and Prevention for Risk Mitigation, **1**: 63-70. Naples: Patron Editore.

Cascini L., Sorbino G., Cuomo S. & Ferlisi S. (2014) - *Seasonal effects of rainfall on the shallow pyroclastic deposits of the Campania region (southern Italy)*. Landslides, **11** (5): 779-792.

Damiano E., Greco R., Guida A., Olivares L. & Picarelli L. (2017) - *Investigation on rainwater infiltration into layered shallow covers in pyroclastic soils and its effect on slope stability*. Engineering Geology.

De Vita P., Napolitano E, Godt J.W. & Baum R.L. (2013) - *Deterministic estimation of hydrological thresholds for shallow landslide initiation and slope stability models: case study from the Somma-Vesuvius area of southern Italy*. Landslides **10** (6): 713-728.

Di Martire D., De Rosa M., Pesce V., Santangelo M.A. & Calcaterra D. (2012) - *Landslide hazard and land management in high-density urban areas of Campania region, Italy*. Nat. Hazards Earth Syst. Sci., **12**: 905-926.

Khire M.V., Benson C.H. & Bosscher P.J. (2000) - *Capillary barriers: design variables and water balance*. J. Geotech. Geonviron. Eng., **126** (8): 695-708.

Landi P., Bertagnini A. & Rosi M. (1999) - *Chemical zoning and crystallization mechanisms in the magma chamber of the Pomici di Base plinian eruption of Somma-Vesuvius (Italy)*. Contributions to Mineralogy and Petrology, **135**: 179-197.

Lappala G., Healy R.W. & Weeks E.P. (1987) - *Documentation of computer program VS2D to solve the equations of fluid flow in variably saturated porous media*. U.S. Geological Survey Water-Resources Investigations, Report **83**: 4099.

Mancarella D. & Simeone V. (2012a) - *Capillary barrier effects in unsaturated layered soils, with special reference to the pyroclastic veneer of the Pizzo d'Alvano, Campania (Italy)*. Bull Eng Geol Environ, **71**: 791-801.

Mancarella D., Doglioni A. & Simeone V. (2012b) - *On capillary barrier effects and debris slide triggering in unsaturated layered covers*. Engineering geology, **147**: 14-27.

Pappalardo L, Piochi M. & Mastrolorenzo G. (2004) - *The 3550 YR BP - 1944 AD magma- plumbing system of Somma-Vesuvius: constraints on its behavior and present state through a review of Sr-Nd isotope data*. Annals of Geophysics, Vol. **47**, n. 4: 1471-1483.

Pappalardo L. & Mastrolorenzo G. (2010) - *Short residence times for alkaline Vesuvius magmas in a multi-depth supply system: Evidence from geochemical and textural studies*. Earth Planet Sci Lett, Doi: 10.1016/j-epsl.2010.05.010.

Pappalardo L., Buono G., Fanara S. & Petrosino P. (2018) - *Combining textural and geochemical investigations to explore the dynamics of magma ascent during Plinian eruptions: a Somma-Vesuvius volcano (Italy) case study*. Contributions to Mineralogy and Petrology, **173**: 61.

Pirone M., Papa R., Nicotera M.V. & Urciuoli G. (2014) - *Evaluation of the hydraulic hysteresis of unsaturated pyroclastic soils by in situ measurements*. Procedia Earth and Planetary Science, **9**: 163-170.

Santacroce R., Cioni R., Marianelli P., Sbrana A., Sulpizio R., Zanchetta G., Donahue D.J. & Joron J.L. (2008) - *Age and whole rock–glass compositions of proximal pyroclastics from the major explosive eruptions of Somma-Vesuvius: A review as a tool for distal tephrostratigraphy*. Journal of Volcanology and Geothermal Research, **177**: 1–18. Sci., 12, 905-926.

Scarfone R. (2020) - *Modelling the hydraulic behaviour of unsaturated soils and application to the numerical and experimental study of capillary barrier systems*. PhD thesis, University of Glasgow.

SEPE C. (2019) - *Landslide susceptibility assessment of pyroclastic deposits in pyroclastic deposits in Campania by modelling of triggering mechanisms*. PhD Thesis, University of Napoli Federico II, Italy.

SHACKELFORD C.D., CHANG C.K. & CHIU T.F. (1994) - *The capillary barrier effect in unsaturated flow through soil barriers*. In: Proceedings of the first international congress on environmental geotechnics. Edmonton, Canada, July 10-15, 1994, 789-793.

STORMONT J.C. & ANDERSON C.E. (1999) - *Capillary barrier effect from underlying coarser soil layer*. J. of Geotech. and Env. Engineering, **125** (8): 641-648.

URCIUOLI G., PIRONE M., COMEGNA L. & PICARELLI L. (2016) - *Long-term investigations on the pore pressure regime in saturated and unsaturated sloping soils*. Engineering geology, **212**: 98-119.

Received February 2021 - Accepted April 2021

