The Role of the Precipitation History on Landslide Triggering in Unsaturated Pyroclastic Soils

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Abstract

A wide area around the town of Naples is mantled by shallow unsaturated volcanoclastic soils that are highly susceptible to fast rainfall-induced flow-like landslides. Some casualties and huge damage recorded in the last twenty years testify the serious threat posed by such events. Due to the impact of these phenomena, the local research community is strongly committed in studies whose results have allowed to understand some key aspects of the triggering and propagation mechanisms. However, the way to run for risk mitigation is still long: given the density of population and of infrastructure, the setting up of reliable early warning systems would be a fundamental tool to this aim. Based on a rich data-base about the features of the rainfall-induced landslides in unsaturated volcanoclastic soils occurred on January, 10th, 1997, in a small area located in the Sorrento peninsula, and the history of precipitations occurred in the same area in the last fifty years, the paper examines the relation between rainstorms and landslides, showing the fundamental role of the recent precipitation history.

Keywords

Rainfall-induced landslide • Unsaturated pyroclastic soils • Precipitation history • Hydrological response • Hazard

Introduction

The hills that rise in a wide area around the town of Naples are mantled by recent layered unsaturated soils of volcanic origin, known as pyroclastic soils. Depending on site, the bedrock consists of older volcanic soils, of fractured limestone or of flysch. The total thickness of the pyroclastic deposits ranges between a few decimeters and a few meters as a function of the slope angle and of the very local morphology. Only the colluvium deposited at the hill foots reaches a thickness of tens of meters.

Due to the low saturation degree of the soil, the stability of steepest slopes is usually granted by matric suction, whose regime is strictly governed by seasonal climate fluctuations. Shallow landslides, often turning into flows, are frequently triggered after intense and persistent rainfall events, that are responsible of suction decrease.

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Many efforts are being made by the local research community to understand the key features of such kind of landslides. In particular, many relevant data have been collected in the last twenty years focusing on the geomorphological context, the key soil properties, the hydrological slope response and the landslide mechanisms (Di Crescenzo and Santo 1999; Olivares and Picarelli 2001; Cascini et al. 2014; Comegna et al. 2016a; Urciuoli et al. 2016).

The study presented here concerns an area located in the Sorrento peninsula that separates the bay of Naples from the bay of Salerno, where four landslides took place on January, 10th, 1997, as a consequence of rainstorms. The availability of rainfall data covering about 50 years, provided by a weather station present in the same area, allowed to examine the role of the precipitation history on the landslides triggering. In particular, the paper analyzes the effects of preparatory and triggering precipitations and proposes some rainfall thresholds.

Basic Properties of the Air-Fall Pyroclastic Soils in the Neapolitan Area

The pyroclastic soils in the area around Naples typically consist of ashes and pumices that in primary air-fall deposits can be found as alternating layers formed during single volcanic events. Figure 1 reports Soil Water Retention Curves (SWRC) obtained from some laboratory tests (Rianna et al. 2014) and field monitoring (Pirone et al. 2014; Comegna et al. 2016a) conducted on different air-fall ashes. The curves present: (i) a typical "stiff" part, which characterises the suction interval from 0 up to about 10 kPa (air entry values), in which the saturation degree remains higher than 95%; (ii) a steep part, up to a maximum suction of 100 kPa, in which the volumetric water content rapidly decreases; (iii) a "stiff" part again, characterized by a strong change in suction induced by a minor decrease in the volumetric water content. The SWRC shows an inflection point at a suction value generally ranging between 5 and 50 kPa. However, the scattering of data is an experimental evidence itself of the fact that the soils present some hydraulic hysteresis (Pirone et al. 2014; Comegna et al. 2015).

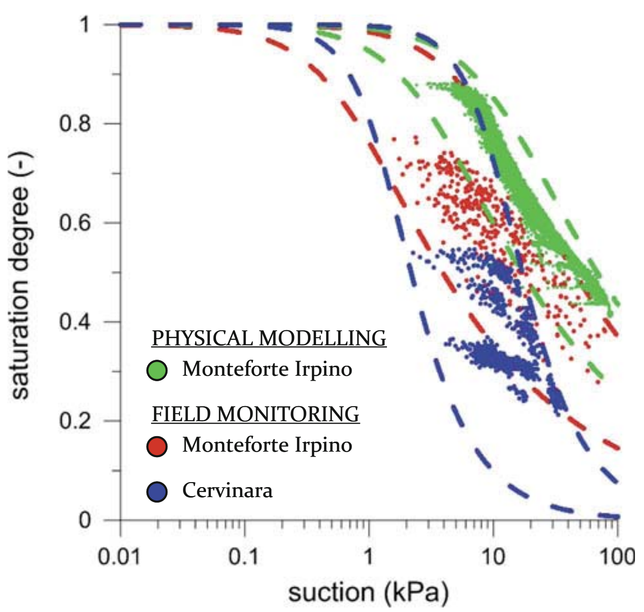

Fig. 1 Soil water retention curves obtained from small-scale physical modelling and field monitoring on different air-fall ashes (modified from Comegna et al. 2016b)

The permeability function, *k*, obtained by Olivares and Picarelli (2003) from some laboratory tests typically covers two or three orders of magnitude ranging from values of $10^{-7} \div 10^{-5}$ m/s (at saturation) to values as low as 10^{-8} m/s, for a suction higher than 80 kPa.

Regarding the shear strength, Olivares and Picarelli (2003) found an apparent cohesion higher than 10 kPa for values of suction higher than 70 kPa; in contrast, the effective cohesion is nil, while the friction angle is about 30°.

The following analyses, aimed at assessing the role of the precipitation history on the hydrological and mechanical response of air-fall pyroclastic ashes present in the Sorrento peninsula, are based on the strong homogeneity of these soils, and exploit the results of the in depth researches briefly summarized in the present section.

The Investigated Cases

Geological and Geomorphological Settings

The Lattari Mts in Sorrento peninsula consist of steep carbonate slopes reaching 1200 m, covered by pyroclastic soils. In the footslopes 35 municipalities with more than 500.000 inhabitants rise: this number is doubled in summertime, because of the presence of several touristic resorts (Amalfi, Positano and Sorrento) thus increasing the risk.

Sorrento peninsula is a structural high, transversal to the Apennines chain, made of Mesozoic carbonates (limestones, dolomitic limestones and dolostones) forming a monocline, generally dipping towards the North. In some areas, Miocene arenaceous-marly-clayey flysch formations outcrop. Pyroclastic soils deposited during the 79 AD Vesuvius eruption mantle the Northern slopes. The overall structural framework of the peninsula is characterized by major normal and inverse faults, mainly NW–SE ("Apennines" trend) and NE–SW ("anti-Apennines" trend) trending. The geomorphological setting of the area is characterized by ancient erosional terraces (paleosurfaces) separated by steep fault scarps, due to the complex interaction between erosion, uplift and block faulting during Plio-Quaternary (Calcaterra and Santo 2004).

The geological and geomorphological setting makes the area prone to landslide. In fact, flow-like events usually involve about 2 m thick pyroclastic soils, with maximum volumes around 60.000 m^3 and velocities of some tens km/h, which in historical time badly affected the towns causing damage and casualties (Di Crescenzo and Santo 1999).

Features of the Landslides of January, 10th, 1997

In the last century, several landslides were induced by heavy and prolonged rainfalls. Table 1 reports the historical events, the daily triggering rainfalls, h_{1d}, and the precipitations accumulated during the previous 90 days, h_{90d}, recorded by local weather stations. All events occurred in Autumn or Winter triggered by 1-day and 90-day cumulative rainfalls respectively ranging in the intervals $0 \div 150$ and $228 \div 1175$ mm. The lowest h_{1d} values are usually associated with the highest h_{90d} values (and vice versa).

Six of the above events occurred on January, 10th, 1997. In particular, four of them, indicated in Fig. 2 as Gragnano (1), Pimonte (2), Corbara (3) and Pagani (4) displayed very similar geomorphological features:

- thickness of the pyroclastic cover around 2 m;
- failure surface located at about 1 m depth;
- mean slope angle around 35°;
- low values of the depth—length ratio (infinite slope).

According to the data provided by the Gragnano weather station (Fig. 2), the Gragnano (1) and Pimonte (2) landslides were induced by a 1-day precipitation h_{1d} = 62 mm and a cumulative 90-day rainfall h_{90d} = 704 mm. Moreover, based on the records of the closer Tramonti Chiunzi weather station (Fig. 2), the Corbara (3) and Pagani (4) landslides were triggered by a similar daily rainfall (h_{1d} = 55 mm) and a higher accumulated precipitation h_{90d} of 1175 mm.

Back-Analysis of the January, 10th, 1997, Events

As shown above, all landslides of January, 10th, 1997, involved shallow deposits of unsaturated pyroclastic soils mantling a calcareous bedrock. The geomorphological features of the outcrops suggested to develop simple 1D

Table 1 Landslides events occurred in the last century in Sorrento peninsula: h_{1d} = triggering daily rainfall event; h_{90d} = cumulative precipitations during the previous 90 days

Date	Municipality	h_{1d} (mm)	h_{90d} (mm)
26-03-1924	Amalfi	54	981
08-12-1960	Pagani	21	682
17-02-1963	Gragnano	38	1057
17-02-1963	Pimonte	38	1057
23-11-1966	Vico Equense	82	630
02-01-1971	Gragnano	66	692
06-03-1972	Pagani	0	867
16-02-1973	Massalubrense	35	544
13-03-1986	Vietri	6	930
10-01-1997	Gragnano (Fig. 2)	62	704
10-01-1997	Pimonte (Fig. 2)	62	704
10-01-1997	Corbara (Fig. 2)	55	1175
10-01-1997	Pagani (Fig. 2)	55	1175
10-01-1997	Castellammare	150	691
10-01-1997	S. Egidio M.	55	1175
05-03-2005	Casola	19	741
05-03-2005	Nocera	19	714
05-03-2005	Ravello	16	712
05-03-2005	Tramonti	20	843
09-09-2010	Scala	129	228
05-03-2011	Amalfi	41	396
01-03-2014	Casola	61	659

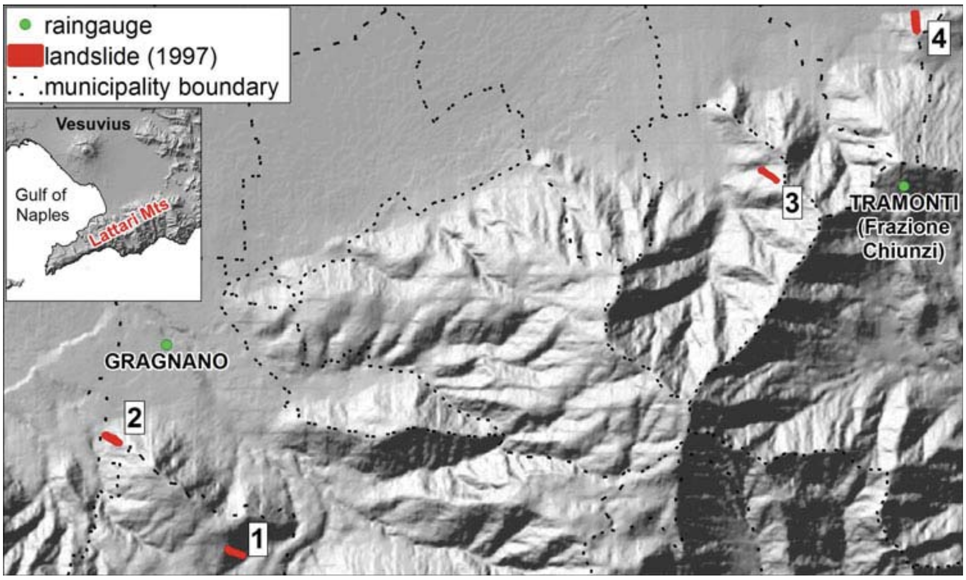

Fig. 2 Location of the studied landslides occurred on January, 10th, 1997: (*1*) Gragnano; (*2*) Pimonte; (*3*) Corbara; (*4*) Pagani

infiltration and stability analyses with the aim to recognize the common hydro-mechanical aspects of those events and to analyze the role of both triggering and recent rainfalls. In the following, the adopted method of analysis is first described, then the main results and tentative rainfall thresholds are reported.

Methods and Data

The landslides have been investigated by stability analyses coupled with seepage simulations. Since the degree of uncertainty associated with the shear strength parameters is much lower than the one related to the hydraulic parameters, the aim of the analyses has been to find reliable combinations of the hydraulic parameters that can justify the events.

The stability analyses have been carried out with the infinite slope model that quite well reproduces the geomorphological features of the slopes. The Factor of Safety, *FS*, at time *t* and critical depth, z_c, is calculated by the equation

$$FS(z_c, t) = \frac{\tan\varphi'}{\tan\beta} + \frac{c' + s(z_c, t)\cdot\Theta(z_c, t)\cdot\tan\varphi'}{sen\beta\cdot\cos\beta\cdot\int_0^{z_c}\gamma(z, t)dz} \quad (1)$$

where Θ is the effective degree of saturation of the soil, γ the unit weight, φ' the effective friction angle, c' the effective cohesion, s the matric suction and β the slope angle. Based on field data described above, the critical depth, z_c, has been set equal to 1 m. The term $s\cdot\Theta\cdot\tan\varphi'$ is the apparent cohesion (Vanapalli et al. 1996).

The current values of Θ, s and γ, required to calculate *FS*, are provided by numerical seepage analyses that have been carried out through the finite element code SEEP/W (GEO-SLOPE International Ltd. 2012) assuming a 1D vertical unit flux in a 2 m thick soil column. The effective infiltration rate and runoff depend on the surface hydraulic conditions governed by the current hydraulic conductivity and gradient. Water infiltration has been simulated by the well known Richards equation (1931). The hydraulic conductivity curve and the soil water retention curve, requested by the code, have been obtained through the simplified van Genuchten (1980)

$$k = \Theta^{0.5}\cdot\left[1 - \left(1 - \Theta^{\frac{1}{m}}\right)^m\right]^2\cdot k_{sat} \quad (2)$$

and

$$\Theta = \left[1 + (\alpha\cdot s)^{\frac{1}{1-m}}\right]^{-m} \quad (3)$$

where k is the current value of the hydraulic conductivity, k_{sat} is the saturated hydraulic conductivity, m and α are empirical parameter. In particular, $\frac{1}{\alpha}$ represents the suction value at the SWRC inflection point, that typically increases with the air entry value.

Table 2 reports the parameters adopted in the analyses. The assumed slope angle is the mean value of the slopes. The assigned soil properties are based on the rich available data base (Picarelli et al. 2007), taking into account the considerable homogeneity of air-fall pyroclastic soils in the region. In particular, constant porosity has been considered thus neglecting the effects of the volumetric collapse that is usual in loose unsaturated soils. Nevertheless, this assumption has been considered suitable since the consequent effect (an increase in both γ and Θ) are opposite in Eq. (1).

Table 2 Soil parameters adopted in the analyses

Parameter	Value
Thickness of the cover, h	2 m
Slope angle, β	35°
Effective cohesion, c'	0
Specific unit weight, γ_s	23.9 kN/m^3
Porosity, n	0.69
Residual saturation degree, S_{res}	0.10
van Genuchten parameter, m	0.60
Saturated hydraulic conductivity, k_{sat}	1E-08 ÷ 1E-06 m/s
Suction value at SWRC inflection point, $\frac{1}{\alpha}$	5 ÷ 50 kPa

Results of the Analyses

In order to reproduce the effects of the 1997 events, some seepage analyses were carried out imposing at the ground surface the precipitation history recorded at the Gragnano weather station (Fig. 2) since January 1st, 1995. With such a procedure the influence of the assumed initial conditions can be disregarded. The analysis was performed imposing an unit vertical hydraulic gradient at the lower boundary, located at the depth z = 2 m: such a simplified hypothesis is not far from the real situation during the wet season (Comegna et al. 2016a).

Regarding the hydraulic soil properties, three different values of k_{sat} (1E-08, 1E-07 and 1E-06 m/s) and six values of $\frac{1}{\alpha}$ (5, 10, 20, 30, 40 and 50 kPa) were adopted to determine the SWRC and the permeability function and eventually calculate a plausible range of the mobilized friction angle, φ'_{mob}, at the critical depth z_c = 1 m, on January, 10th, 1997. Figure 3 shows that: (i) for any value of $\frac{1}{\alpha}$, φ'_{mob} decreases with k_{sat}; (ii) the same occurs with $\frac{1}{\alpha}$ for any value

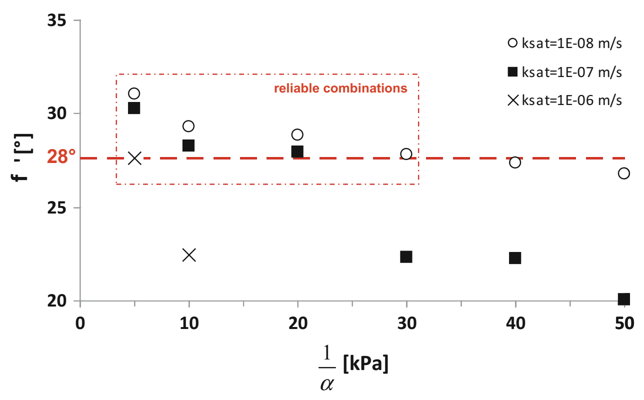

Fig. 3 Back-calculated values of the friction angle, φ', according to different k_{sat} and $\frac{1}{\alpha}$ values

of k_{sat}. In particular, eight combinations (dashed rectangle in Fig. 3) lead to a mobilized friction angle equal or higher than 28°, which can be considered the minimum likely value accounting for the soil nature.

Once calibrated the model, the subsequent step has been the assessment of the precipitation-induced landslide hazard in the examined area. To this aim, further analyses were carried out for the eight plausible combinations of the hydraulic soil parameters considering all precipitations monitored at the Gragnano weather station from January, 1st, 1952 to December, 31st, 1999. Therefore, eight different daily FS values were calculated over 48 years. Such values have then been averaged in order to obtain the daily mean slope safety factor $\overline{FS}$. Finally, a probabilistic relationship between antecedent precipitations and $\overline{FS}$ was determined as explained in the next section.

Landslide Hazard Assessment

Methods and Data

A homo-schedastic (constant standard error) bi-variate linear regression method has been adopted for estimating the calculated average daily slope safety factor $\overline{FS}$ as a function of the daily rainfall event, h_{1d}, and the precipitations accumulated during the previous 90 days, h_{90d}. Arguably, none of those two monitored precipitations alone can be used to predict the slope's safety factor. This leads to the estimation of conditional mean $E(\overline{FS}|h_{1d}, h_{90d})$ and standard deviation $\sigma(\overline{FS}|h_{1d}, h_{90d})$ of the average safety factor as a function of the rainfall records h_{1d} and h_{90d}

$$E(\overline{FS}|h_{1d}, h_{90d}) = a_o + a_1 \cdot h_{1d} + a_2 \cdot h_{90d}$$
$$\sigma(\overline{FS}|h_{1d}, h_{90d}) = \sqrt{\frac{\sum_{i=1}^{n}\left(\overline{FS}_i - E(\overline{FS}|h_{1d}, h_{90d})\right)^2}{n-3}} \quad (4)$$

where n is the number of data points and a_o, a_1 and a_2 are linear regression coefficients.

Figure 4 shows the data points and the regression plane fitted to the data according to Eq. (4). The goodness of fit can be measured by the coefficient of determination R^2 which is an estimate of the percentage reduction in dispersion achieved by the regression

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(\overline{FS}_i - E(\overline{FS}|h_{1d}, h_{90d})\right)^2}{\sum_{i=1}^{n}\left(\overline{FS}_i - E(\overline{FS})\right)^2} \quad (5)$$

The closer is the coefficient of determination to unity, the more efficient is the regression in reducing the variance.

Individuation of Rainfall Thresholds

Assuming that the distribution of the average safety factor, given h_{1d} and h_{90d}, is Normal (i.e. Gaussian), the probability of slope failure, given h_{1d} and h_{90d}, can be calculated as follow

$$P_F = P(\overline{FS} < 1 | h_{1d}, h_{90d}) = \Phi\left(\frac{1 - E(\overline{FS} | h_{1d}, h_{90d})}{\sigma(\overline{FS} | h_{1d}, h_{90d})}\right) \quad (6)$$

where $\Phi(.)$ is the standard Gaussian cumulative distribution function and $E(\overline{FS} | h_{1d}, h_{90d})$ and $\sigma(\overline{FS} | h_{1d}, h_{90d})$ can be estimated from Eq. (4). Equation (6) can be very useful for estimating the domains of h_{1d} and h_{90d} which correspond to the probability of slope failure or "failure probability" P_F varying in a certain prescribed range. For instance, defining three thresholds of *attention*, *alert* and *alarm* as P_F equal to 0.005 (0.50%), 0.01 (1%) and 0.05 (5%), respectively, one can derive four domains of *safety*, *attention*, *alert* and *alarm* as illustrated in Fig. 5.

The comparison of the measured triggering precipitations h_{1d} and h_{90d} (Table 1) with the derived thresholds shows that the absolute majority of the previous landslide events would have triggered the "alarm" status; one event would have triggered the "alert" status and two events (9%) would have been missed by the system as false negative alarms. It's worth noting that, according to the gained alarm threshold (Fig. 5), the triggering is strongly governed by the preparatory precipitations (related to the h_{90d} values), while it seems less influenced by the features of the triggering events (associated to the h_{1d} values).

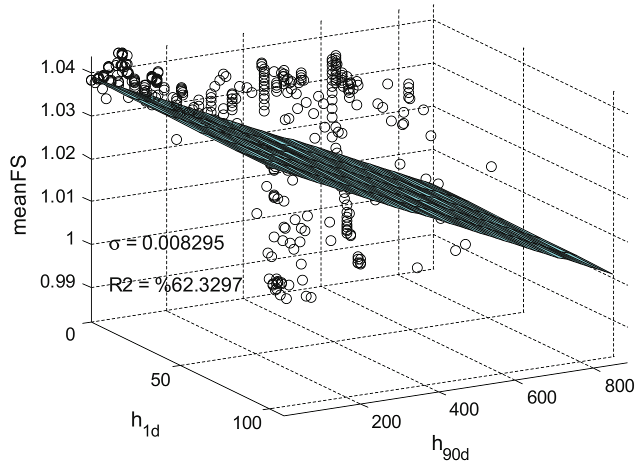

Fig. 4 The bi-variate linear regression fit to the calculated average safety factor of the slope

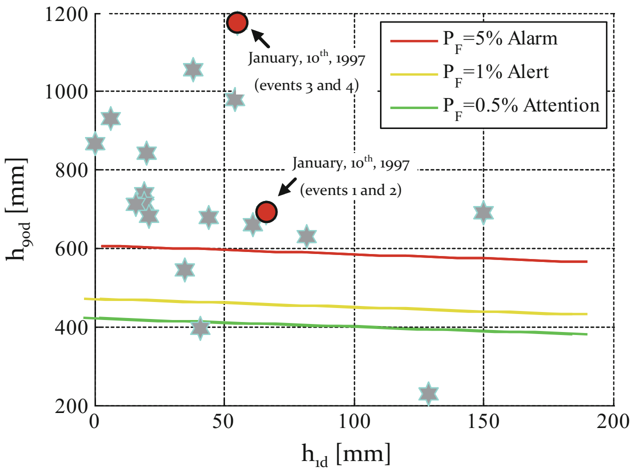

Fig. 5 Calculated thresholds of attention (*green*), alert (*yellow*) and alarm (*red*): the "*circles*" correspond to the January, 10th, 1997, triggering rainfalls; the "*stars*" correspond to the data related to the other landslides occurred in the Sorrento peninsula (see Table 1)

Conclusive Remarks

Based on the knowledge of the main features of some rainfall-induced landslides occurred in a small area located in the Sorrento peninsula (Campania Region, Italy) and the availability of the record of precipitations in the last fifty years, an investigation has been carried out around the relations between rainfalls and landslide hazard. The estimated rainfall thresholds for the examined area stress the predominant role of the precipitation history.

References

Calcaterra D, Santo A (2004) The January 10, 1997 Pozzano landslide, Sorrento Peninsula Italy. Eng Geol 75:181–200

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 11:779–792

Comegna L, Damiano E, Greco R, Guida A, Olivares L, Picarelli L (2015) Investigation on the hydraulic hysteresis of a pyroclastic deposit. In: Proceedings of the international workshop on Volcanic Rocks and soils, 24–25 September 2015. Lacco Ameno, Ischia Island, pp 161–162

Comegna L, Damiano E, Greco R, Guida A, Olivares L, Picarelli L (2016a) Field hydrological monitoring of a sloping shallow pyroclastic deposit. Can Geotech J 53(7):1125–1137

Comegna L, Rianna G, Lee G, Picarelli L (2016b) Influence of the wetting path on the mechanical response of shallow unsaturated sloping covers. Comput Geotechnique 73(3):164–169

Di Crescenzo G, Santo A (1999) Geomorphologic analysis of the slide-flows in the pyroclastic deposits of the Sorrento Peninsula (Campania). Geogr Fis Din Quat 22:57–72 (in Italian)

GEO-SLOPE International Ltd. (2012) SEEP/W user's guide. Canada

Olivares L, Picarelli L (2001) Susceptibility of loose pyroclastic soils to static liquefaction: some preliminary data. In: Proceedings of the international conference landslides—causes, impacts and countermeasures. Davos, pp 75–85

Olivares L, Picarelli L (2003) Shallow flowslides triggered by intense rainfalls on natural slopes covered by loose unsaturated pyroclastic soils. Geotechnique 53(2):283–288

Picarelli L, Evangelista A, Rolandi G, Paone A, Nicotera MV, Olivares L, Scotto di Santolo A, Lampitiello S, Rolandi M (2007) Mechanical properties of pyroclastic soils in Campania Region. In: Proceedings of 2nd international workshop on characterisation and engineering properties of natural soils, vol 3. 29 November–1 December 2006, Singapore, pp 2331–2383

Pirone M, Papa R, Nicotera MV, Urciuoli G (2014) Evaluation of the hydraulic hysteresis of unsaturated pyroclastic soils by in situ measurements. Procedia Earth Planetary Sci 9:163–170

Rianna G, Pagano L, Urciuoli G (2014) Investigation of soil-atmosphere interaction in pyroclastic soils. Journal of Hydrology 510:480-492

Richards LA (1931) Capillary conduction of liquids through porous mediums. Physics 1(5):318–333

Urciuoli G, Pirone M, Comegna L, Picarelli L (2016) Long-term investigations on the pore pressure regime in saturated and unsaturated sloping soils. Eng Geol 212:98–119

van Genuchten T (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44:892–898

Vanapalli SK, Fredlund DG, Pufahl DE, Clifton AW (1996) Model for the prediction of shear strength with respect to soil suction. Can Geotech J 33:379–392