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Matric suction in unsaturated pyroclastic slopes

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ABSTRACT: In situ measurements of matric suction in the pyroclastic covers of four slopes in Naples, which were susceptible to debris flows, were conducted from 2000 to 2005. The water level is several hundred meters below the ground surface. The measured suctions were used to calibrate a numerical hydrological model, which referred to the first four meters of depth that could be affected by flow movements. The volcanic soil of the cover consists of loose deposits of ashy and coarse levels that originated from the recent activities of the Campi Flegrei (Phlegrean Fields). The bedrock is made of Volcanic Tuff (mainly Neapolitan Yellow Tuff). This model makes it possible to reproduce the seasonal cycle of suction in the pyroclastic cover in the study area and could be used to assess an early warning system as part of risk management procedures.

1 LANDSLIDES

In the city of Naples there are hilly areas of variable height (h) ranging from the 100 to 500 m which are partly exposed to the sea and partly located in urbanized areas. These slopes consist of a rocky skeleton of volcanic nature (tuffs of different age) and are covered by pyroclastic products of the activity of the Third Phlegrean period (<12,000 years), illustrated in Figure 1. The latter are characterized by alternations of ash and lapilli deposits. They are characterized by high porosity (mean void ratio $e = 1.28$, st. dev. = 0.23) and are partially saturated (mean degree of saturation $Sr = 0.46$ st. dev. = 0.15). The ticks are very variable, ranging from one meter to some tens of meters on the hills of Camaldoli and Posillipo, and up to several tens of meters in the Conca di Agnano.

In such areas landslides are widespread (Beneduce et al., 1988; Pellegrino, 1994; Calcaterra and Guarino, 1999; Scotto di Santolo, 2000a; 2002). The standard type of the phenomena is for 30% complex landslides (translational or rotational slide, or falls that lead to debris flows). The volumes are generally reduced (reaching the maximum rates of 1000 m^3) and only in some cases do the covered distances (L) exceed the foot of the hill (Lmax = of 300 m). The geometric feature of landslides is compared in Figure 2 with what occurred in the Campania region (Monti Lattari and Monti di Sarno) in recent years. It is observed that the distance covered increases with the difference in height between the crown and the toe of landslides H with a linear relationship for H less than 400 m whereas it increases with a power law for H greater than 500 m.

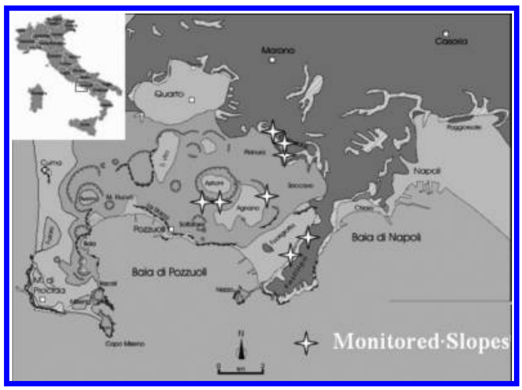

Figure 1. Location of monitored slopes on the geological map of Campi Flegrei (modified from Isaia et al, 2004).

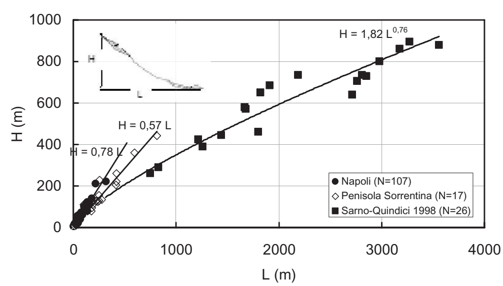

Figure 2. Relation between travel distance and difference between the height of the crown and the toe of the deposits of debris flows (modified from Scotto di Santolo, 2002).

Moreover, for the same H the mobility is a function of a travel path (Scotto di Santolo and Evangelista, 2008). The reach angle (arctan(H/L)) is constant and equal to 38°. Nevertheless the risk is high because of the intense urbanization of the hilly area, Figure 3.

The landslides occurred in the rainy period: in Figure 4 the frequency of the landslides in the months of the year are reported for 101 complex landslides which occurred in this deposit in the period between 1986 and 2009 (November). It has been observed that the phenomena mainly take place in winter (the maximum are recorded in January, most of them in January 1997) and the beginning of spring. If compared with average monthly rainfall, as shown in Figure 5, it can be observed that the landslides do not occur in correspondence with the wetter period (October–December), but are delayed by several months. By defining the recurrence of landslides as the ratio between the period of time in which these events took place and their number, it was calculated that this time is less than 10 years in the study area.

The delay between rainfall and landslides is a function of climatic conditions and the hydraulic characteristics of the cover which, since it is partially saturated, has a conductivity that varies with water content (Scotto di Santolo and Evangelista, 2009).

The triggering of landslides is strongly related to rainfall: the increase of water content in soil is the principal undisputed factor leading to soil failure (e.g. Lumb, 1962; Iverson, 2000; Scotto di Santolo et al., 2000).

Infiltration of rainfall leads to a decrease in suction which reduces the shear strength of the shallow soil (e.g. Fredlund et al., 1978; Evangelista & Scotto di Santolo, 2001). The prediction of triggering factors is of extreme importance for hazard mitigation, due to the dynamic features that characterize these phenomena during their evolution.

Figure 3. View of the Astroni Volcano, Naples, showing the high level of urbanization of the hilly zones.

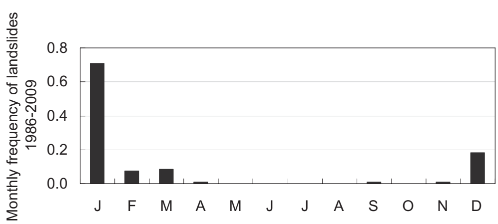

Figure 4. Distribution of landslides (1986–2009).

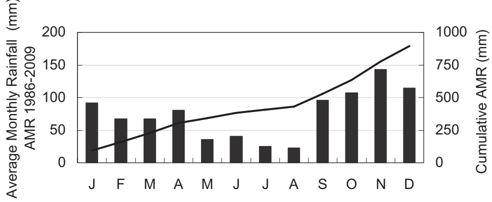

Figure 5. Average monthly rainfalls (1986–2009).

2 DESCRIPTION OF MONITORING SYSTEM

Four sites which are representative of the morphologic and stratigraphic conditions of slopes susceptible to debris flows in Naples were monitored with rain gauges, tensiometers, psychrometers, tiltmeters and TDR probes (Evangelista et al., 2003). Two sites are situated on the hill of the Camaldoli, the highest relief in the city (456 m asl), one on the hill of Posillipo and one in the basin of Agnano (Figure 1). All sensors were automatically recorded every hour in routine conditions and the data was sent by modem to a remote computer. The measurements began in February 2000 and were completed in June 2005.

It represents one of the first installations (if not the first) for continuum measurements of suction in a pyroclastic cover in southern Italy. Unfortunately the inexperience with the use of innovative equipment (the first in 2000) and initial uncertainties did create some problems. Moreover maintenance always was not carried out on a continuous basis with the result that some instruments were often desaturated for long periods. Therefore some stations sometimes lack readings.

The stations that worked best were S1 and the S2 during the period 2001–2003 and therefore reference is repeatedly made to them. For all of them temporary measuring devices were also available and were used to gain a more complete and wider picture of the phenomenon.

In Figure 6 the time histories of average daily readings on the tensiometers are reported

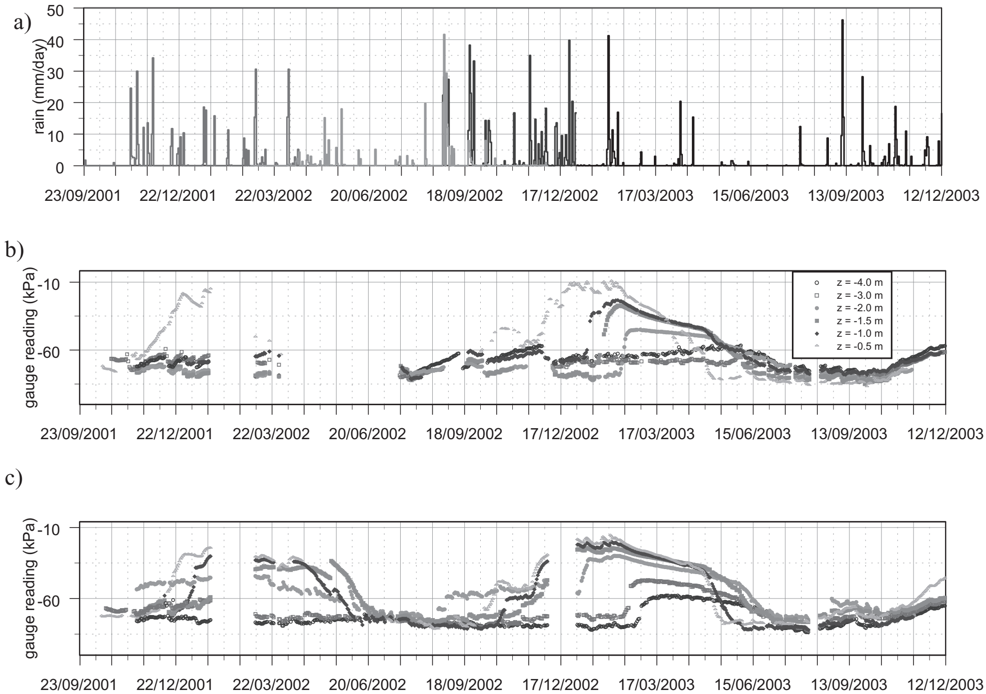

Figure 6. Results of monitoring: a) rainfall; b) and c) average values at gauge readings on the tensiometers at S1 and S2 sites.

for the stations S1 and S2 for each depth of measurement (0.5; 1; 1.5; 2; 3; 4 m from the p.c.). It was observed that the response at 0.5 m from the surface is closely related to rainfall (also shown in Figure 6a). A delay was recorded according to depth. Therefore while the suction reaches the minimum at 0.5 m in the winter months, at 2.0 m the minimum is reached at the beginning of spring. For greater depths (3–4 m) less variation was observed so that it was considered to be fairly constant, with the exception of the measurements taken in the spring of 2002.

3 MATRIC SUCTION REGIME

This paragraph provides a review of the available suction data, and a hydraulic model of infiltration that explains the seasonal cycles of the suctions in the pyroclastic soil is presented.

3.1 *Review of the suction data*

The data available in all sites was collected and interpreted in terms of daily averages for each depth (0.5; 1.0; 1.5; 2.0; 3.0 and 4 m).

The data, reported in Figure 7, were interpolated from sinusoidal functions of a period equal to a year. The results of the statistical analysis are shown also in the diagrams in Figure 7.

The best fit for the statistical model varies according to the depth and the time interval T considered. For each year the coefficient R^2 and the standard deviation are estimated by comparing the observed data with the calculated data. The results for all depths are shown in Table 1.

As already mentioned, the measurements were often interrupted due to the desaturation of the equipment. This is reflected by the goodness of the fitting parameters of the statistical model.

3.2 *Hydrological model*

The governing flow equation for one-dimensional conditions in an unsaturated rigid porous medium is given by the modified form of the Richards' equation:

$$\frac{\partial \theta(\psi)}{\partial t} = \frac{\partial}{\partial z}\left(K(\psi)\frac{\partial \psi}{\partial z} + K(\psi) \right) \qquad (1)$$

where θ is the volumetric water content, ψ is the pressure head (negative for unsaturated soil), K is the hydraulic conductivity, z is a vertical coordinate positive upward and t denotes time.

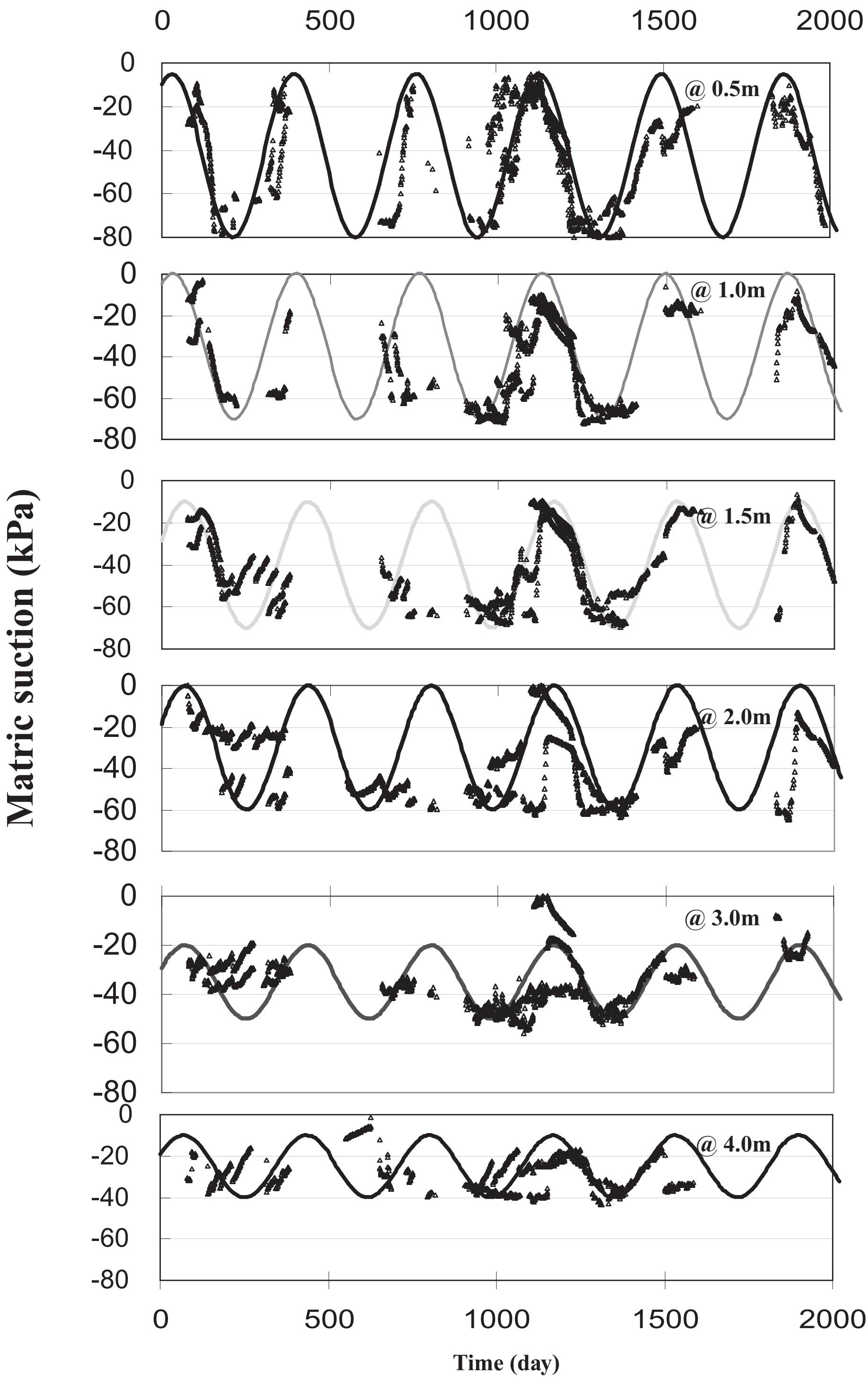

Figure 7. In situ suction measurements (years 2000–2005) and fitting functions at each depth.

Table 1. Statistical variability of the data and time for which there is the best correlation.

Depth from s.l. (m)	Average in situ suction (kPa)	R^2 (1)	T (d)	Dev. St. (kPa)	T (d)
0.5	41	0.87	1460 ÷ 1825	8.00	279 ÷ 644
1	41	0.87	1460 ÷ 1825	8.10	937 ÷ 1302
1.5	41	0.99	1460 ÷ 1825	1.95	1004 ÷ 1469
2	37	0.61	1460 ÷ 1825	8.44	662 ÷ 10279
3	34	0.88	1460 ÷ 1825	4.30	383 ÷ 718
4	27	0.1	243 ÷ 608	9.80	594 ÷ 959

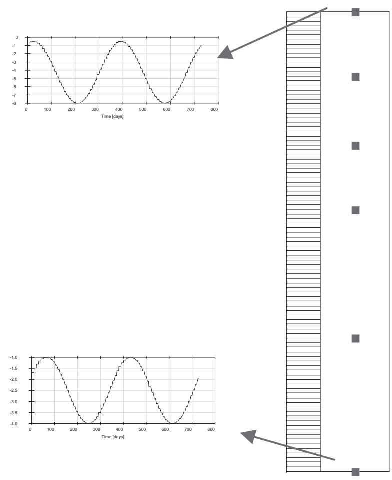

Figure 8. Sketch of boundary conditions.

This equation was solved with the finite-element model HYDRUS 1D code (Simunek et al., 2005) using the well-known constitutive relation proposed by van Genuchten (1980). The stratigraphy and soil parameters were obtained by the authors in previous works (Scotto di Santolo et al., 2005).

The model was implemented on the basis of the measurements of suction that were carried out. Time histories of suction in a shallower and deeper layer were used as boundary conditions (0.5 and 4 m; Figure 8). The suctions calculated for the intermediate depths (1,0; 1.5; 2.0; 3.0 m) were then compared with those measured.

This approach is useful because it does not take into account the quantification of the water infiltration of the precipitation and does not require simulation of the evaporation and runoff. The procedure derives from the observation that infiltration is conditioned by the shallower layers of the ground, which are extremely variable due to their properties, and by the type and density of vegetation.

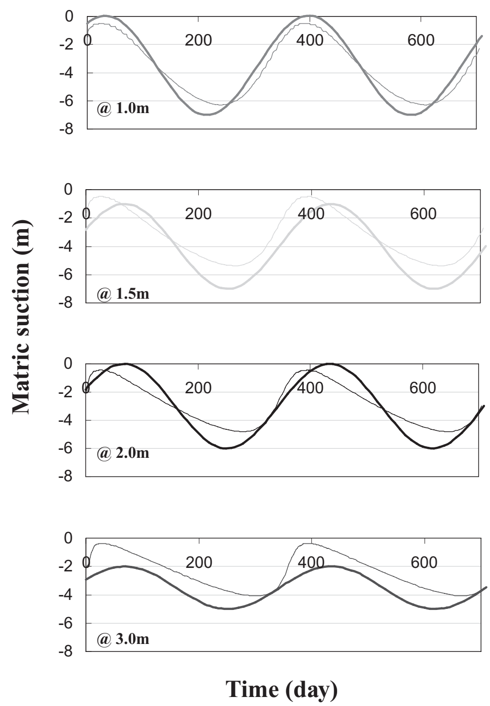

Figure 9. Comparison between in situ suction and the calculated data at intermediate depth.

3.3 *Comparison between the hydrological model and in situ measurements*

The calculated suction time histories, expressed in days, are reported in Figure 9 together with the measured ones (1.0 m, 1.5 m, 2.0 m and 3.0 m). We obtained a satisfactory correspondence between measurements and the calculated data, even though the desired coincidence was not possible in cases where the control parameters were highly variable.

4 CONCLUDING REMARKS

In situ measurements of matric suction in four slopes which are susceptible to debris flows in

Naples, Italy, were used to calibrate a numerical hydrological model.

The analyzed data provided the mean value of matric suction during the five-year period 2000–2005 and therefore does not consider situation details which can be verified or which may happen.

The measurements and their interpretation enabled us to making some useful considerations about setting up a warning system in order to forecast the trigger conditions of landslides in partially saturated soils.

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