Analysis and Field Monitoring of Slope Stability in Unsaturated Pyroclastic Soil Slopes in Napoli, Italy

Aldo Evangelista
Università degli Studi di Napoli Federico II – Italy, Naples, Italy

Anna Scotto di Santolo
Università degli Studi di Napoli Federico II – Italy, Naples, Italy

Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

ANALYSIS AND FIELD MONITORING OF SLOPE STABILITY IN UNSATURATED PYROCLASTIC SOIL SLOPES IN NAPOLI, ITALY

Aldo Evangelista
Dipartimento di Ingegneria Geotecnica
Università degli Studi di Napoli Federico II – Italy
Naples, Italy

Anna Scotto di Santolo
Dipartimento di Ingegneria Geotecnica
Università degli Studi di Napoli Federico II – Italy
Naples, Italy

ABSTRACT

The hills rising in the urban area of Napoli (Italy) are the products of eruptive activity in the volcanic areas of *Campi Flegrei* and *Somma Vesuvio*. The unsaturated pyroclastic cover, weathered and interbedded with paleosols, is frequently affected by instability phenomena that have slight thickness and extension. The observed landslides can be classified as complex phenomena: the movements start as a translational or rotational sliding or as a rock-fall and evolve as the debris flows. 90% of the cases occur during or after severe rainfalls. As is well known, the stability of slopes is affected by climatic conditions, such as rainfall and evapotranspiration, which affect the matric suction near the ground surface. A slope analysis requires that an in situ matric suction profile be measured or predicted. A monitoring system was therefore developed to collect data on suction profiles in pyroclastic soils. Four slopes, chosen as representative of morphological, geological and geotechnical triggering conditions in the studied area, were outfitted with rain gauges, vacuum tensiometers, psychrometers, tiltmeters and TDR gauges.

INTRODUCTION

The hills rising in the urban area of Naples, Italy are the products of eruptive activity in the volcanic areas of *Campi Flegrei* and *Somma Vesuvio*. Pyroclastic soils (pozzolana) generally overlay the lithic part of the formation (Neapolitan Yellow Tuff and other tuffs). The upper layer of pyroclastic un-cemented deposits, which is a few meters' deep, is weathered and interbedded with paleosols. Usually these deposits are well above the groundwater table and hence are under unsaturated conditions.

These hills are frequently affected by slope instability phenomena of small thickness and extension. The observed landslides can be classified as complex phenomena (Cruden & Varnes, 1996) in 30% of reported cases (in total, nearly 300 phenomena were identified from 1986 to 1999 de Riso et al., 1999). The movements start as a translational or rotational sliding or as a rock-fall and evolve as the debris flows. These small-volume phenomena present a limited total horizontal reach (less than 300 m) and a quite constant mobility, unlike that of the 1998 Sarno landslide (Scotto di Santolo, 2002a). In 90% of the cases, landslide phenomena occurred during or after severe weather during the wet season (Evangelista & Scotto di Santolo, 2003).

As is well known, slope stability is affected by climactic conditions such as rainfall and evapotranspiration, which control the changes of matric suction near the ground surface. The plane infinite slope analysis, incorporating matric suction, has most widely been used for the determination of natural hill slope stability, particularly where the soil cover is shallow compared to the slope length and the potential surface is planar (Fredlund & Rahardjo, 1993). Unfortunately, this simplified analysis also requires that the in situ matric suction profile during rainfall be measured or predicted. The seepage of rainwater into a slope is a very complex problem that depends on rainfall characteristics, slope geometry, soil properties and type of vegetation. In steep slopes with a deep groundwater table, the negative pore water pressure (or matric suction) plays a positive role in affecting the shear strength of the soil and thus increases the stability of the slopes. Results of laboratory testing on unsaturated pyroclastic soils confirm that water infiltration is the mechanism leading to slope failures since it reduces the matric suction in the unsaturated soil and hence reduces its shear strength (Scotto di Santolo, 2000a, b; Evangelista & Scotto di Santolo, 2001). With the significance of pore pressure in mind, a monitoring system was developed to collect data on suction profiles in pyroclastic soils. Four slopes, chosen as representative of morphological, geological and geotechnical conditions in the studied area, were fitted with rain gauges, vacuum tensiometers, psychrometers, tiltmeters and TDR gauges.

This paper discusses only tensiometer suction measurements; besides quantifying matrix suction directly, they allow the determination (given the relation between suction and shear strength) of the time-varying shear strength under unsaturated conditions.

SUCTION EFFECT ON SLOPE STABILITY

The relationship between rainstorms and landslides is well recognized and numerous examples have been reported in the literature from all over the world: Brazil (De Costa, 1969); Hong Kong (Lumb, 1962; Brand et al., 1984); Italy (Cascini & Versace, 1986); Japan (Fukuoka, 1980; Haruyama, 1980), New Zeland (Crozier, 1969). Very few studies of the triggering mechanism are present in the literature. The role of suction in the triggering mechanism has been pointed out by Terzaghi (1950), quantified by Lumb (1962) and further investigated by a number of other researchers (e.g. Burland & Ridley, 1996). Furthermore, the effects of rainfall on soil suction profiles and the role of suction in unsaturated slope stability has been investigated more recently by means of in situ measurements (e.g. Johnson and Sitar, 1990; Jucà et al., 1995; Fredlund et al., 1995; Lim et al., 1996; Gasmo et al, 1999; Faisal, 2000; Yagi et al 2000; Evangelista et al, 2001, Cascini & Sorbino, 2002), and theoretical and numerical analyses (e.g. Rahajardo et al., 1996; Fourie et al. 1999; Gasmo et al., 2000; Harrison and Blight, 2000; Tsaparas and Toll, 2002).

Despite this great research effort, currently available prediction tools are not yet able to estimate correctly the influence of rain on soil suction profiles and hence predict instability phenomena reliably. This lack of reliability is due essentially to the difficulties either in determining some soil properties (e.g. permeability function, characteristic curve, etc.) or in defining initial (i.e. the suction and water content initial profile) and boundary conditions (e.g. evaporation and infiltration fluxes, run-off, etc.). Clearly more field measurements should be collected in order to calibrate theoretical tools more suitably. However, great difficulties can arise from in situ monitoring; Ridley and Wray (1995) observed that although a great number of experimental fields has been equipped all over the world, the only known long-term field sites still in operation are in Brazil, China and USA.

Further difficulties arise during experimental determination of the shear strength and suction relationship. Though laboratory equipment has been developed to measure suction, testing times are high. Available relations of the form $\tau = f(\text{suction})$ are mainly applicable towards clayey lime soils reconstructed in the lab. The literature contains several theoretical and experimental relations for estimating shear strength from saturated material strength and angle φ_b (eg. Fredlund et al., 1978) or the characteristic curve (e.g. Vanapalli et al., 1996).

At present, available data for characterizing Neapolitan pyroclastic soils is limited (e.g. Evangelista et al., 2002). Therefore the following analysis refers to the relationship proposed by Fredlund et al., (1978) briefly reported below:

$$\tau_f = c' + (\sigma - u_a) \cdot \tan\varphi' + (u_a - u_w) \cdot \tan \varphi_b \quad (1)$$

where

τ_f = shear strength;

$(\sigma - u_a)$ = net normal stress, equal to the difference between total pressure and air pressure;

c' and φ' = effective strength parameters,

$(u_a - u_w)$ = matrix suction pressure, equal to the difference between air pressure and water pressure (from in situ measurements);

$(u_a - u_w) \cdot \tan\varphi_b$ = apparent cohesion, which represents the suction's contribution to shear strength for an unsaturated soil.

FIELD MEASUREMENTS IN THE HILLS OF NAPOLI

Four slopes in the urban area of Napoli were chosen as representative of morphological, geological and geotechnical triggering conditions. Two of the investigated sites are situated on Camaldoli hill (Pianura side), one on Posillipo hill (Fuorigrotta side), and one in the Agnano valley (respectively indicated as A, B, C, D in the following).

Instrumentation of these slopes was used to monitor either in situ suction or slope movements, and to verify the influences that meteorological events have on them up to depths of 4m.

The monitoring system consists of rain gauges, tensiometers, psychcrometers, tiltmeters and TDR gauges (Time Domain Reflectometry) (Evangelista et al., 2001).

A sketch of a typical soil profile and of instrumentation layout is reported in Figure 1. All 116 instruments are equipped with electrical gauges connected to an automatic data logger which records readings every hour, for a total of 2784 readings per day. Remote interrogation and data acquisition is carried out by means of a modem. The measurements started in February 2000 and continue to the time of this writing.

The tensiometers are vacuum-type (Soil Moisture, California) and are currently under evaluation for their accuracy in pyroclastic soils. In particular, observations in the first year of monitoring showed that the matric suction measurements, after apparently reaching equalisation, did not remain stable but systematically decreased regardless of meteorological conditions (figure 2). Furthermore, water ran out from some of the instruments, rendering them unusable. Careful inspection of the water-level maintenance logs showed that the shallowest tensiometers were rapidly emptied. After verifying the integrity of the porous capsules and the correct installation of the instrumentation, the tensiometer's functionality was investigated in the laboratory (Evangelista et al., 2003).

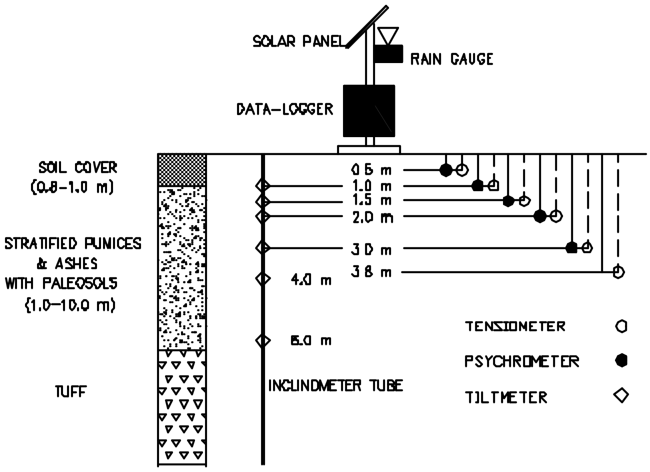

Figure 1. Sketch of a typical soil profile and instrumentation layout.

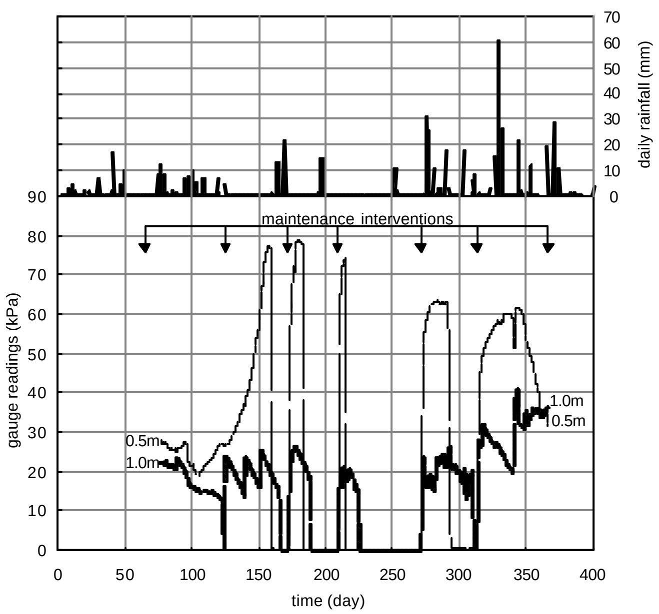

Figure 2. Rainfall characteristics and suction response at site B during year 2000: rainfall gauge readings and matric suction measurements at 0.5 e 1.0m depths.

A series of controlled laboratory tests was carried out to investigate the air accumulation phenomenon and to estimate the response time of a vacuum tensiometer when buried in pyroclastic material.

A vacuum tensiometer, a TDR gauge and a PT100 gauge were buried in the soil sample in a thermo-regulated room and temperature was monitored by means of an electronic gauge. The response times of the vacuum tensiometer corresponding to different soil suction values were experimentally determined at the end of each drying or wetting step. The gauge readings subsequent to a number of air flushing operations were used to evaluate equalisation time interval while air cavity expansion in the tensiometer was recorded during each phase in which water content remained constant in order to estimate air growth rate (Evangelista et al., 2003).

Consistent with laboratory results, intensified maintenance operations were scheduled (up to one every 7-15 days depending on weather conditions) and modified flushing procedures put in place to improve reliability of field measurements. Figure 3 shows matric suction measurements carried out at site B over a one-month period. One maintenance operation was carried out in the considered time period. The improvement in reading stability is quite evident. In addition, the diagram shows that the response of the tensiometers was almost immediate and that air flushing produced small fluctuations in the readings.

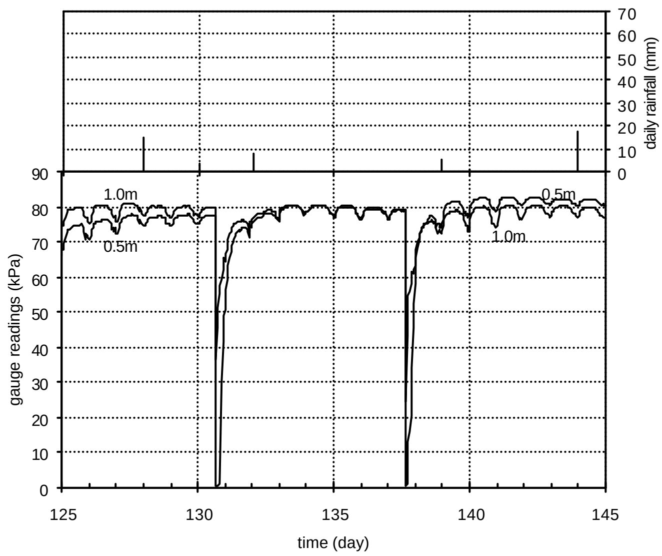

Figure 3. Improvements in suction measurements at at site B.

MATRIC SUCTION MONITORING

Figure 4 shows the current year's default measurement reading schedule for the six stations placed at different depths along with rainfall data. Most of the variations in suction and changing meteorological conditions, especially temperature, are evident at 0.5 m from the ground surface. Instruments between one and two meters deep show a decreasing profile from January to early February, a trend slightly muted at greater depths, with a then increasing profile until June. Suction readings at three and four meters' depth were nearly constant around 40 and 30 kPa respectively.

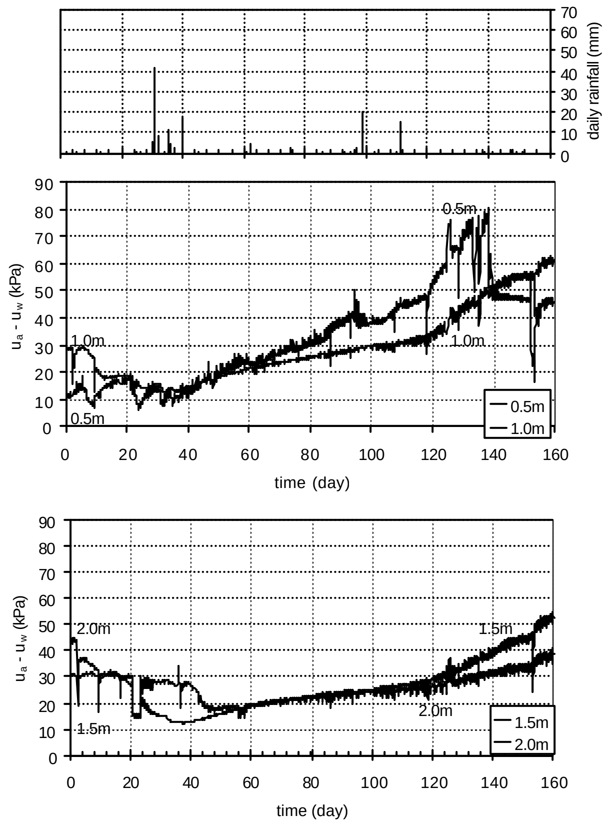

Figure 4. Mean of suction measurements of the monitored sites during 2003

The measurements carried out allow for the determination of slope stability conditions as a function of rainfall. In particular, the minimum suction values measured durnig three years, which scalably represent the available resistance according to Fredlund et al (1978), were recorded during various meteorological events in January and April. The heavier rainfall recorded occur inMay 2003; though resulting in higher suction variations, did not reach the minimum required for landslide onset due to the period's overall dry spell (Scotto di Santolo, 2002b).

PRELIMINARY ASSESSMENTS OF SLOPE STABILITY WITH RESPECT RAINFALL

Stability conditions were arrived at through a parametric study in terms of total stress by considering a infinite homogeneous soil slope (β). Taken into consideration as possible sliding surfaces were planes parallel to the indefinite slope model and circular surfaces for varying values of thickness (f) to length (l) ratios of circular landslide bodies taken from geological reliefs of previous landslide events in the area (de Riso et al, 1999).

By holding φ, γ and the slip surface depth (z) constant, the necessary cohesion (c_n) was calculated such that SF =1 for varying β and f/l.

The cohesion required (c_n) has been plotted in Figure 5 as a function of the ratio tgφ/tgβ for φ = 35° and γ = 15kN/m^3, for varying values of the ratio f/L, and slip surface depth equal to z= 0.5 and 3 m.

The undefined slope model results in the highest cohesion values. Comparison with available laboratory data (Evangelista et al., 2002; Olivares et al., 2002) shows that landslide events could have occurred only under near-saturated material strength..

These figures were used to evaluate stability conditions for the areas of interest under various weather conditions. A former study was used to set the f/L ratio and z. A study of these slopes values corresponding to 90% of landslide areas.

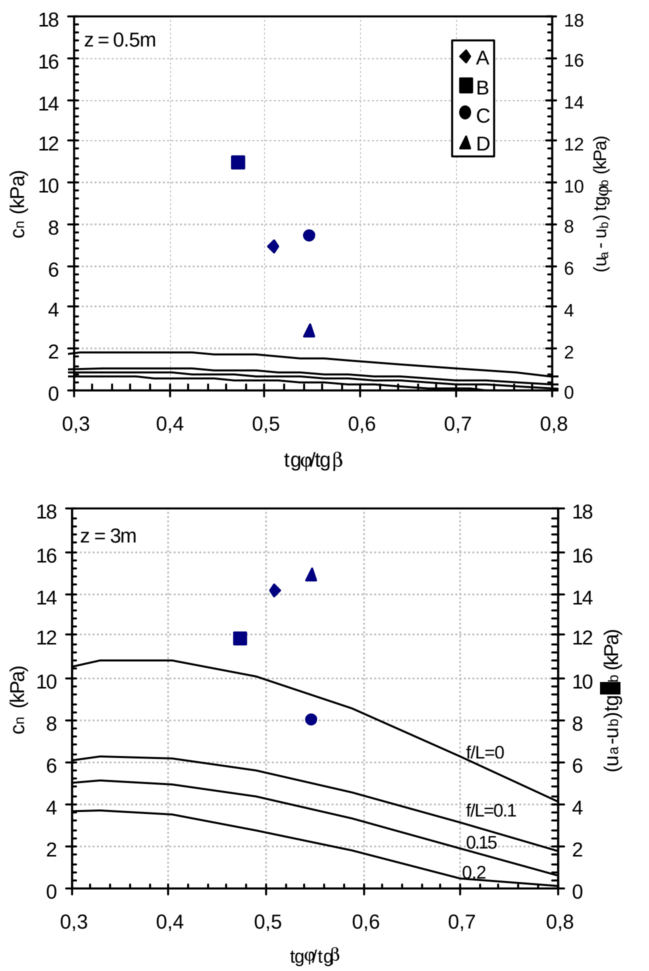

Figure 5. Cohesion necessary c_n e apparent cohesion during the rainy season: for z= 0,5 and for z= 3m.

From the in-situ minima matric suction measurements the apparent cohesion values has been calculated according relation (1) (Fredlund et al., 1978). Note that the matrix suction referred to in calculating the apparent cohesion is the mean of the measurements taken from tensiometers placed above the hypothetical sliding surface by assuming a surface suction equal to that measured at z=0.5 m.
The figure 5 shows also these apparent minimum cohesion values at the 90% slope mark of the slide area under consideration.
It may be observed that over the three-year measurement period, critical conditions (SF=1) were never reached, which is entirely in line with the fact that no landslide phenomena occurred in the monitored area.
The exception to this can be found in Site C for sliding surfaces parallel to the slope with z=3m.

CONCLUSION

Field suction measurements in the pyroclastic cover of some slopes in the city of Naples, Italy were carried out for more than three years. Early measurementss were affected by a number of uncertainties. As a result, vacuum tensiometer performance were investigated in-depth both theoretically and experimentally. Consistent with laboratory results, different maintenance procedures were developed and implemented. These procedures made it possible to overcome the uncertainties which initially affected the in situ suction measurements (Evangelista et al., 2003).
It was thus possible to use the suction readings to evaluate stability conditions for the four monitored slopes by considering the matrix suction's contribution to stability over time.
Available measurements, some continuous and others scheduled regularly, prove of notable importance in defining an alarm system for the prediction of landslides triggered by rainfall in the areas of interest.

ACKNOWLEDGEMENT

The Authors wish to thank Prof. Arturo Pellegrino for his valuable assistance in planning the research presented. Funding for this research was provided by the Murst – PRIN 2001 "*Mitigazione del rischio di frana in aree antropizzate. Interventi di stabilizzazione e gestione del territorio*".

REFERENCES

Brand E.W., J. Premchitt, H.B. Phillipson. [1984]. Relationship between rainfall and landslides in Hong Kong. *Proc. 4th ISL*, Canadian Geotechnical Society, Toronto, Vol. 1, 377-384.

Burland J.B., A.M. Ridley [1996]. The importance of suction in soil mechanics. 12th Southeast Asian Geotecnical Conference, Kuala Lumpur.

Cascini L, P. Versace [1986]. Eventi pluviometrici e movimenti franosi. *Atti del XVI Convegno Nazionale di Geotecnica*, Bologna.

Cascini L., G. Sorbino [2002]. Soil suction measurements over large areas, a case study. *Proc. of the 3rd International Conference on Unsaturated Soils*, UNSAT 2002, Recife, Brasil, 829-834.

Crozier M.J. [1969]. Eartflows occurence during high intensity rainfall in eastern Otago. *Engineering geology*, 3, 325-334.

Cruden D.M., D.J. Varnes [1996]. Landslides types and processes. in *Landslides, Investigation and Mitigation*, Special Report 247, Cap III, 36-75, 1996.

De Costa A.J. [1969]. Landslides in soils of decomposed rocks due to intense rainstorms. *Proc. 7th Intern. Conference on Soil Mechanics and Foundation Engineering*, Mexico city, 2, 547-554.

de Riso, R., P. Budetta, D. Calcaterra, A. Santo [1999]. Debris flows in pyroclastic deposits of Campanian territory. *Atti Conv. su "Previsione e prevenzione di movimenti franosi rapidi"*, Trento, 133-150, GEAM. (in Italian)

Evangelista A., A. Pellegrino, A. Scotto di Santolo [2001]. Misure in sito di suzione nelle coltri piroclastiche del napoletano. in *Campi sperimentali per lo studio della stabilità dei pendii*, (Evangelista & Pellegrino ed.) Benevento Hevelius, pp. 19-25.

Evangelista, A., A. Scotto di Santolo [2001]. Mechanical Behaviour of unsaturated pyroclastic soil. *Proc. Landslides: Causes, Impacts and Countermeasures*, Davos-Switzerland.

Evangelista A., M.V. Nicotera, A. Scotto di Santolo [2002]. Caratteristiche geotecniche dei terreni piroclastici della città di Napoli. *Atti del XXI Convegno Nazionale di Geotecnica*, L'Aquila, pp. 45-52.

Evangelista A., M.V. Nicotera, A. Scotto di Santolo [2003]. Experimental and Theoretical validation of matric suction measurements in pyroclastic soils. *Proc. of International Conference on Fast Slope Movements prediction and prevention for risk mitigation*, IC-FSM 2003, Napoli, Italy.

Evangelista, A. & A. Scotto di Santolo [2003]. Field measurements of matrix suction profiles in Neapolitan pyroclastic soil slopes, *Proc. 2nd ASIAN Conference on Unsaturated Soils*, UNSAT-ASIA 2003, Japan.

Faisal H.A, [2000]. Unsaturated tropica residual soils and rainfall induced slope failures in Malaysia. Proc. of the Asian Conference on Unsaturated soil, UNSAT-ASIA 2000, Singapore, 41-52.

Fourie A.B. [1996]. Predicting rainfall-induced slope instability. Geotech. Engng., 119, 211-218.

Fourie A.B., D. Rowe, G.E. Blight [1999]. The effect of infiltration on the stability of the slopes of a dry ash dump. *Géotechnique*, 49, 1, 1-13.

Fredlund D.G., N.R. Morgenstern, R.A. Widger [1978]. The shear strength for unsaturated soils. *Canadian Geotechnical Journal*, 15, 313-321.

Fredlund D.G., H. Rahardjo [1993]. Soil mechanics for unsaturated soils. Wiley Sons, Toronto.

Fukuoka M. [1980]. Landslides associated with rainfall. *Geotechnical Engineering*, 1980, 11, 1-29.

Gasmo J.M., K.J. Hritzuk, H. Rahardjo, E.C. Leong [1999]. Instrumentation of un unsaturated residual soil slope. *Geotechnical Testing journal*, 22, 2, 134-143.

Gasmo J.M., H. Rahardjo, E.C. Leong [2000]. Infiltration effects on stability of a residual soil slope. *Computers and Geotechnics*, 26, 145-165.

Harrison B.A., G.E. Blight [2000]. A comparison of in situ soil suction measurements. *Proc. of the Asian Conference on Unsaturated soil*, UNSAT ASIA 2000, 281-285.

Haruyama M. [1980]. Mass movements in the slopes with pyroclastic deposits. *Proc. of Int. Symposium on Landslides*, New Delhi, 55-58.

Johnson K.A., N. Sitar [1990]. Hydrologic conditions leading to debris-flow initiation. *Canadian Geotech. J.*, 27, 789-801.

Jucà J.F.T., J.M. Justino da Silva, J.A. Gusmao Filho, E. G. Bastos [1995]. Laboratory and field tests on an unsaturated expansive clay, *Proc. of the 1st Intern. Conference on Unsaturated soil* UNSAT'95, Paris, Vol 2, 877-884

Lim T.T., H. Rahardjo, M.F. Chang, D.G. Fredlund [1996]. Effect of rainfall on matric suctions in a residual soil slope. *Can. Geotech. Journal*, 33, 618-628.

Low H., A. Faisal [2000]. Suction and infiltration measurements on cut slope in highly heterogeneous residual soil. *Proc. of the Asian Conference on Unsaturated soil*, UNSAT ASIA 2000, 807-811.

Lumb P. [1962]. The effect of rainstorm on slope stability. *Proc. Symposium on Hong Kong soils*, 78-87.

Olivares, L., L. Picarelli, L. Andreozzi, B. Avolio, E. Damiano, S. Lampitiello [2002]. Scenari di pericolosità di frana in terreni sciolti di natura piroclastica. *Atti del XXI Convegno Nazionale di Geotecnica*, L'Aquila, 173-181.

Rahajardo H., M.F. Chang, T.T. Lim [1996]. Stability of residual soil slopes as affected by rainfalls. *Landslides*, Balkema, 1109-1114.

Rassam D.W., D.J. Williams [1999]. A relationship describing the shear strength of unsaturated soils, *Canadian Geotechnical Journal*, 36, 363-368.

Ridley A.M., W.K. Wray [1995]. Suction measurement: A review of the current theory and practices. *Proc. 1st International Conference on Unsaturated Soils*, Paris, Vol 3, 1293-1322.

Scotto di Santolo A. [2000a]. Analisi geotecnica dei fenomeni franosi nelle coltri piroclastiche della Provincia di Napoli. *Ph.D. thesis*, Naples & Rome University.

Scotto di Santolo A. [2000b]. Analysis of a steep slope in unsaturated pyroclastic soils. *Proc. Asian Conference on Unsaturated Soils*, Singapore, 2000, 569-574.

Scotto di Santolo A. [2002a]. *Le colate rapide*. Hevelius Ed., Benevento.

Scotto di Santolo A. [2002b]. Regime delle pressioni neutre nelle coltri piroclastiche dei versanti della città di Napoli. Influenza sulle condizioni di stabilità. *Grant post Ph.D.* C.U.G.RI.

Soil moisture equipment corp. [1986]. Model 2725 a jet fill tensiometer operating instructions. Soil moisture equipment corp. Santa Barbara, CA.

Terzaghi K. [1950]. Mechanism of landslides. Application of Geology to Engineering Practice, Geological Society of America, New York, 83-123.

Tsaparas I., D.G Toll. [2002]. Numerical analysis of infiltration into unsaturated residual soil slopes. *Proc International Conference on Unsaturated soils*, Recife, Brazil.

Vanapalli S.K., D.G. Fredlund, D.E. Pufahl, A.W. Clifton [1996]. Model for the prediction of shear strength with respect to soil suction. *Can. Geotech. J.* 33: 379-392.

Yagi N., R. Yatabe, K. Yokota, N.P. Bhandary [2000]. Suction measurement for the prediction of slope failure due to rainfall. *Proc. of the Asian Conference on Unsaturated soil*, UNSAT-ASIA 2000, Singapore, 41-52.