Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY
© 2024 the Authors
ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-234
Open Access: www.taylorfrancis.com, CC BY-NC-ND 4.0 license

ECSMGE 24
XVIII EUROPEAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

An early warning procedure based on coupling short-time weather forecasting and numerical slope analysis

Un système de early warning basé sur le couplage prévision météo à court-terme - analyse numérique du comportement de la pente

M. Pirone*, G. Forte, A. Santo, G. Urciuoli
Università degli Studi di Napoli "Federico II", Naples, Italy

L. Picarelli
Centro Euro-Mediterraneo per i Cambiamenti Climatici, Italy

**marianna.pirone@unina.it*

ABSTRACT: Rainfall-induced debris flows and avalanches represent an impending hazard in some densely populated areas of Campania Region, Italy, which are mantled by loose air-fall volcanic ashes. The development of reliable early warning systems is then a strong need. The studies that have been carried out in the last twenty years, which include the long-lasting monitoring of some well instrumented slopes, have allowed to obtain a good knowledge about the hydraulic and mechanical properties of these soils. A further step should be now the assessment in real time of their response to expected rainfall aimed at setting up reliable early warning systems. A procedure that exploits the available short-term weather forecasts and a numerical analysis of the potential slope response to rainfall based on field monitoring of the initial conditions, is proposed.

RÉSUMÉ: Les coulées de debris induites par les précipitations représentent un risque permanent dans certaines zones densément peuplées de la Region Campanie, en Italie, qui sont caractérisées par des couvertures de cendres volcaniques lâches de déposition aérienne. Le développement de fiables systèmes de early warning est donc un impératif. Les études qui ont été conduits dans les vingt dernières années, qui ont inclus la surveillance à long terme de quelques pentes bien instrumentées, ont permis de obtenir une bonne connaissance du comportement hydraulique et mécanique du sol. Une nouvelle étape maintenant devrait être l'évaluation en temps réel de leur réponse aux précipitations prévues, dans le but de développer des fiables systèmes de early warning. Dans cet article on propose un processus qui utilise les prévisions météo à court-terme disponibles et l'analyse de la réponse potentielle de la pente aux précipitations sur la base de la surveillance sur site des conditions hydrauliques initiales.

Keywords: Unsaturated volcanic ash; rainfall forecasting; field monitoring; numerical analysis.

1 INTRODUCTION

Sudden and destructive rainfall-induced debris flows and avalanches represent an impending hazard in some densely populated areas of Campania Region, Italy, which are mantled by loose air-fall volcanic ashes. The development of reliable early warning systems is then a strong need. The studies which include in depth hydraulic and mechanical characterization of the soil and long-lasting monitoring of some well instrumented slopes, have allowed to obtain a good knowledge about the properties (Lampitiello, 2004; Nicotera et al., 2015; Dias et al., 2022) and behaviour of these soils (Comegna et al., 2016; Picarelli et al., 2020; Pirone et al., 2023). In order to protect people and infrastructure, a further step should be now the assessment in real time of their response to expected rainfall aimed at setting up reliable early warning systems. This paper describes a novel procedure based on the numerical analysis of the potential slope response to expected rainfall in the next hours by exploiting official weather forecasts and data provided by field monitoring, which can provide the initial hydraulic conditions. Here, first, the soil properties and the numerical model employed, with a focus on model validation, are presented; then, in order to assess if the proposed approach can be effectively used within early warning systems, results of some blinded analyses carried out in a monitored site in Campania, are shown.

2 THE INVESTIGATED AREA AND THE MAIN SOIL PROPERTIES

The proposed approach is applied in the area of Pagani (SA), 35 km South-East from Naples, in a site where some debris flows have occurred in the past. The stratigraphic setting consists of a 2 m deep succession of thin air-fall pyroclastic soil layers covering a fractured carbonate bedrock (Santo et al., 2021). Bottom upward in the considered section (Figure 1a), the succession includes 20–60 cm thick silty sands (C1), overlaid by brown silty sands rich in pumices (A2), which have a thickness of 30–130 cm. The top soil consists of a highly weathered vegetated volcanic ash (A1); its thickness spans from 20 to 80 cm, with a mean value around 35 cm. The average slope angle is 35°.

The instrumentation consists of four tensiometers and four TDR probes installed in pairs at the same depth (Figure 1a). Matric suction and volumetric water content are being measured hourly since November, 2020. The site is also equipped with a rain gauge that records rainfall every ten minutes.

The pyroclastic cover is partially saturated over the entire year. Figure 1b shows the grain-size curves obtained from a number of samples; the curves fall within the envelopes of the pyroclastic soils of the whole Lattari chain (Santo et al. 2021) and of the Faito Mt. test site (Pirone et al., 2023). Considering that the Mt. Faito soils have the same geological history, stratigraphy and porosity as the Pagani soils, here we have assumed also the same friction angle (Table 1). The hydraulic properties have been obtained by processing field data collected at the Pagani test site and are summarized in Figures 2a, b. The solid lines in Figure 2a show the Water Retention Curves (WRCs) obtained by interpolating hourly field data, provided by tensiometers and TDR probes over the first part of the year 2021, by the Van- Genuchten model (crossed lines).

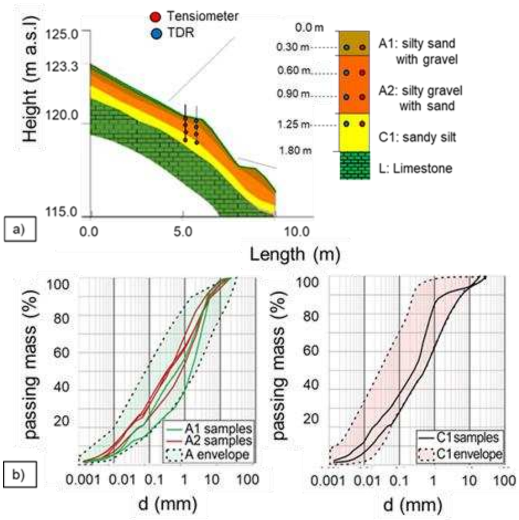

Figure 1. a) Longitudinal section of the slope, simplified stratigraphic soil profile, the instruments installed in the Test Site; b) Grain-size curves of soils A1, A2 and C1 along with the envelopes of the other samples collected on Lattari Mts.

Table 1. Mean physical and mechanical properties of soils sampled in Mt. Faito (γ_d: dry unit weight; n: soil porosity; φ':friction angle at critical state).

Soil	γ_d (kN/m^3)	n (-)	φ' (°)
A1	7.70	0.70	38.4
A2	8.19	0.65	38.4
C1	7.35	0.70	35.4

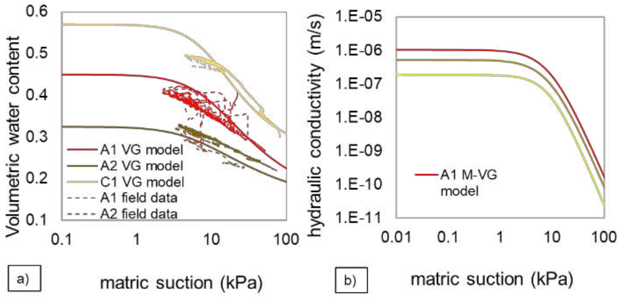

Figure 2. a) WRCs of single layers, as adopted in the analysis, compared to field data; b) HCs of single layers. In the figure M-VG means Mualem Van Genuchten.

The corresponding Hydraulic Conductivity curves (HCs, Figure 2b) have been obtained according to the modified Mualem-Van Genuchten function (Mualem, 1976). For what concerns the saturated permeability of layers A2 and C1, it has been assumed to be equal to the average value measured at the Monte Faito test site through constant head permeameter tests. Finally, the saturated permeability of layer A1 has been taken as a calibration parameter for the numerical model, adopting the value that best replicates the in-situ measurements of suction and water content.

3 RELIABILITY OF THE NUMERICAL ANALYSIS

The hydraulic slope response to precipitation has been investigated by means of the Richards' equation implemented in the FEM code SEEP/W using the WRCs and the HCs (Figs. 2a-b).

The longitudinal slope section shown in Figure 1a has been modeled through a mesh with element sizes of 0.05 m. In order to test the model's effectiveness, the effects of some rainy events recorded from winter 2021 to winter 2022, have been simulated by applying at the upper boundary the hourly rainfall measured by the rain gauge installed at the Test Site and neglecting evapotranspiration. The numerical simulations focus solely on rainstorm duration, adopting hourly time steps. The matric suction values measured in the pyroclastic cover before rainstorms have been assigned as initial conditions. It is useful to outline that the initial suction retains a memory of the slope's past hydraulic history. In all the analyses, the lower boundary and the edges of the domain have been modeled as potential seepage faces, which keep null flux for pore pressure < 0 kPa, and convert the boundary condition to a head-type, with the total head, H, equal to the y-coordinate (which means assuming u = 0 kPa) when u > 0 kPa. Several numerical analyses have been carried out as the saturated hydraulic conductivity of layer A1 varies in the range of $5\cdot10^{-7}$ - $5\cdot10^{-6}$ m/s, which represents a reasonable interval of variation for the hydraulic conductivity of pyroclastic soils. The value of $1\cdot10^{\wedge-6}$ m/s resulted in the lowest mean error, *e*, defined as the difference between the measured and calculated value. Field vs calculated values of matric suction and volumetric water content at depths of 0.30 m and 1.25 m during four selected rainfall events are plotted in Figure 3 along with the values of *e* and of standard deviation of *e*, noted as dev.st (*e*). The good match between recorded and calculated values, which are characterized by *e* lower than 1 kPa for matric suction and equal to 0.015 for average volumetric water content, is encouraging. However, as expected, a greater standard deviation has been calculated for the topsoil (0.30 m) due to the difficulty to replicate the complex phenomena related to the soil-atmosphere interaction by means of this simple numerical model.

This indicates that, in principle, both the numerical approach and the soil properties used in the analysis allow to properly predict the slope response to rainfall.

4 THE PROPOSED EARLY WARNING PROCEDURE

The proposed procedure has been tested using the weather forecast provided by 3Bmeteo.com for April 16, 2023, rainfall, made 48h and 24h before respectively, i.e., on April, 14, and April, 15. Calculated and measured values of matric suction and volumetric water content are plotted in Figures 4a-d. Figures 4e and f, in turn, show the factor of safety (FS) calculated by uploading the predicted suction distribution in the code SLOPE/W that implements the limit equilibrium method (LEM). The contribution of matric suction to shear strength has been obtained through the equation proposed by Vanapalli et al. (1996). The critical shear surface has been determined by imposing the entry and exit option. The minimum thickness of the zone, within which the sliding surface may develop, has been set at a depth of 0.5 m based on evidence. The safety factors corresponding to rainfall forecast 48h and 24h before the selected day (April, 16) are compared to the safety factors determined under the rainfall that has been actually recorded.

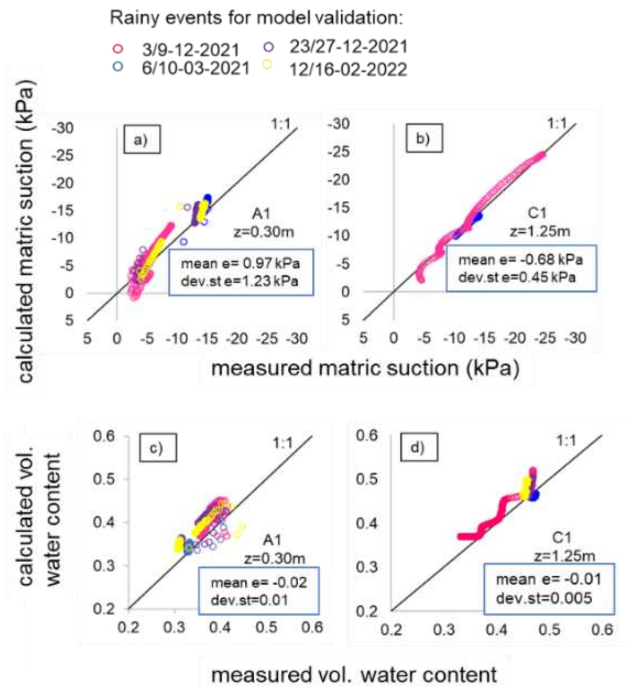

Figure 3. a), b) Measured vs calculated values of matric suction at depths of 0.30 m and of 1.25m; c), d) volumetric water content at the same depths.

As field readings show, almost the entire soil cover is subjected to suction decrease due to both the amount of rainfall and the high hydraulic conductivity of the soil in such a wet period. It is worth noting that suction at 0.30 m continues to increase even after rainfall stops. The corresponding factor of safety (FS) along with the critical slip surface are shown in Figures 4e and 4f. The maximum thickness of the involved soil body is 0.90 m (within the soil A2), and FS reflects the suction trend of the uppermost half part of the pyroclastic cover.

The daily rainfall forecasted 48h and 24h before April, 16, were 19 mm and 35.2 mm respectively, less than the value that was actually measured at the Test Site (42 mm). The analysis shows that rainfall forecast 24h before can provide a better prediction of the hydraulic slope response (Figure 4b,d), leading to FS values closer to those that have been determined under the recorded rainfall (Figure 4f). In contrast, the rainfall forecast 48h in advance underestimates the decrease in matric suction by providing FS values about 40% higher (FS=1.50 against FS=1.22) than those calculated for the actual rainfall distribution (Figure 4a, c, e). Since the capability to correctly assess the suction distribution from measured rainfall appears to be quite good (Figure 3), these results show that, at the moment, a major problem concerns the reliability of weather forecast, which strongly depends on the selected time interval in advance.

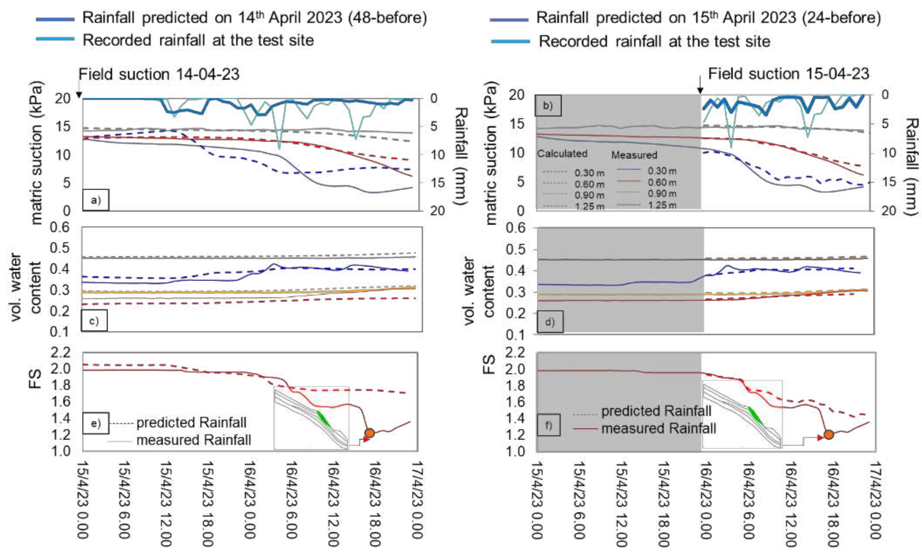

Figure 4. a), b), c), d) Measured (solid line) and predicted values (dashed line) of suction (a and b) and of volumetric water content (c and d) on April, 16, 2023, based on rainfall forecast 48 h and 24h in advance; e), f) safety factor, FS, calculated from measured and forecasted Rainfall along with the picture of critical slip surface determined for FS corresponding to measured Rainfall.

5 CONCLUSIONS

A numerical procedure for early warning of fast flow-like rainfall-induced landslides in unsaturated pyroclastic soils based on weather forecast and field monitoring of the initial soil conditions, is being tested in an area susceptible to slope failure. The first results are encouraging showing that the reliability of the approach strongly depends on a correct forecast of the rainfall amount and distribution. At the moment, further in-depth analyses are needed to have a clear understanding about the reliability and effectiveness of the procedure proposed.

REFERENCES

Comegna, L., Damiano, E., Greco, R., Guida, A., Olivares, L., Picarelli, L. (2016). Field hydrological monitoring of a sloping shallow pyroclastic deposit. *Can. Geotech. J.,* 53: 1125–1137. https://doi.org/10.1139/cgj-2015-0344.

Dias, A.S., Pirone, M., Nicotera, M.V., Urciuoli, G. (2022). Hydraulic hysteresis of natural pyroclastic soils in partially saturated conditions: experimental investigation and modelling. *Acta Geotech.,17*:837–855. https://doi.org/10.1007/s11440-021-01273-y.

Lampitiello, S. (2004). *Resistenza non drenata e suscettività alla liquefazione di ceneri vulcaniche della Regione Campania.* PhD Thesis, Seconda Università di Napoli.

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resour. Res.,* 12(3): 513–522. http://dx.doi.org/10.1029/WR012i003p00513.

Nicotera, M.V., Papa, R., Urciuoli, G. (2015). The hydro-mechanical behaviour of unsaturated pyroclastic soils: an experimental investigation. *Eng.Geol.*,195:70–84. https://doi.org/10.1016/j.enggeo.2015.05.02.3

Picarelli, L., Olivares, L., Damiano, E., Darban, R., and Santo, A. (2020). The effects of extreme precipitations on landslide hazard in the pyro clastic deposits of Campania region: A review. *Landslides,* 17 (10): 2343–2358. https://doi.org/10.1007/s10346-020-01423-5.

Pirone, M., Di Maio, R., Forte, G., De Paola, C., Di Marino, E., Salone, R., Santo, A., Urciuoli, G. (2023). Study of the groundwater regime in unsaturated slopes prone to landslides by multidisciplinary investigations: Experimental study and numerical modelling. *Eng. Geol.,* 315, 107045. https://doi.org/10.1016/j.enggeo.2023.107045.

Santo, A., Pirone, M., Forte, G., De Falco, M., Urciuoli, G. (2021). Slope Stability Assessment of the Test Site in Pagani (Campania, Southern Italy). *Lecture Notes in Civil Engineering*, 156:359–365. https://doi.org/10.1007/978-3-030-74258-4_23.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E., Clifton, A.W. (1996). Model for the prediction of shear strength with respect to soil suction. *Can. Geotech.* J., 33:379–392. https://doi.org/10.1139/t96-060.

INTERNATIONAL SOCIETY FOR
SOIL MECHANICS AND
GEOTECHNICAL ENGINEERING

This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

https://www.issmge.org/publications/online-library

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 18th European Conference on Soil Mechanics and Geotechnical Engineering and was edited by Nuno Guerra. The conference was held from August 26th to August 30th 2024 in Lisbon, Portugal.