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Modelling landslides induced by rainfall: a coupled approach

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Abstract

Landslides induced by rainfall represent a significant natural hazard for large part of Europe. The catastrophic flowslides that occurred on steep slopes in Campania (southern Italy) in 1998, 1999, and 2005 were triggered by rainwater infiltration into shallow deposits of pyroclastic soils, which were initially unsaturated. In this work we present a back analysis at two different scales on the effects of infiltration into a layer of pyroclastic soils. The evolution of pore water pressure, water content and displacement has been monitored at laboratory scale in a flume test and *in situ* in the Cervinara slope located North-East of Naples. In the back analysis of flume test, a fully hydro-mechanical model has been used to describe the behaviour of the pyroclastic soils from unsaturated to saturated condition. In the case of Cervinara slope, the soil-atmosphere interaction has been modelled as a boundary fluxes which take into account the thermo-hydro-mechanical interaction based upon fundamental physics.

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Keywords: Landslides, Collapsible soils, Thermo-hydro-mechanical modelling, Soil-atmophere interaction, Benchmark

1. Introduction

This paper presents the prediction made by UPC research group as part of a collaborative piece of research undertaken by different universities to benchmark the hydrological response of small-scale physical model and the data from a well-instrumented natural slopes (details see http://www.iwl.unina2.it/). The results have been presented during the third Italian Workshop on Landslides (IWL) in which one session has been dedicated to a Round Robin

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Test on landslide hydrological modelling. The benchmarking exercise is based on data monitored at two different scales: an infiltration flume test done in controlled laboratory conditions and the monitoring of Cervinara slope under atmospheric conditions[1]. The modelling at the two scales are presented in the paper using a fully coupled thermo-hydro-mechanical model implemented in a finite element code (CODE_BRIGHT[2]).

2. Infiltration flume test

The infiltration flume test is an instrumented mock-up experiment realized on loose granular volcanic ashes from Cervinara, a mountainous area North-eastern of Naples, Italy. The main characteristics of the tests reproduced in this work are reported in Table 1. More details can be found in Greco et al (2010)[3]. Data provided in the benchmark contains:

1) Geometry, initial and boundary conditions of the test to be predicted
2) Experimental data of the water retention curves, obtained either directly in the pressure plate apparatus and in suction controlled triaxial tests or indirectly from the back-analysis of transient permeability tests.
3) Measurements obtained during two reference tests (labelled D3 and D4) realized in the same mock-up.

The retention curve has been obtained from relationship between degrees of saturation and suctions measured at different depths in test D4. It is depicted in Figure 2 and compared with the retention curve determined from laboratory data. The discrepancy is analyzed to result from the difference in density and anisotropy[4] between both data sets. Permeability parameters have then been calibrated by back-analyzing. Once fixed the water retention curve, the hydraulic model has been calibrated by back-analyzing the intrinsic permeability (5.28e-5 m/s) and the relative permeability function from the time evolutions of pore pressure measured in tests D3 and D4.

In order to predict the rainfall-induced displacements and their effects on the hydraulic response of the soil stratum, the hydraulic model has been then coupled to a mechanical constitutive model. An enhanced formulation of the original CASM model developed by Yu (1998)[5] has been used. This formulation, developed by Gonzalez (2011)[6], includes a dependency of the yield envelope of the material on suction, according to the framework developed by Alonso et al. (1990)[7]. An interesting feature of the model is the flexible definition of the shape of the yield envelope, which allows well-reproducing the shear strength of the material on the dry side of the critical state. Table 2 indicate the parameters and the values used for the mechanical behaviour of the soil.

Table 1. Characteristics infiltration flume test

Test	Soil thickness (cm)	Slope length (cm)	Initial porosity	Rainfall intensity (mm/h)	Initial mean suction (kPa)	Duration of the test (min)
D3	10	100	0.75	55	17.5	36
C4	10	110	0.65	60	52	-

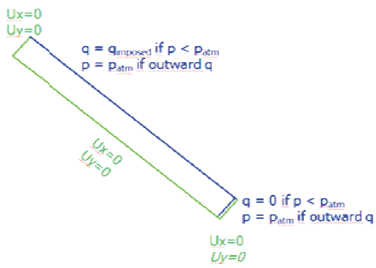

Fig. 1. Geometry and boundary conditions considered in the small-scale model.

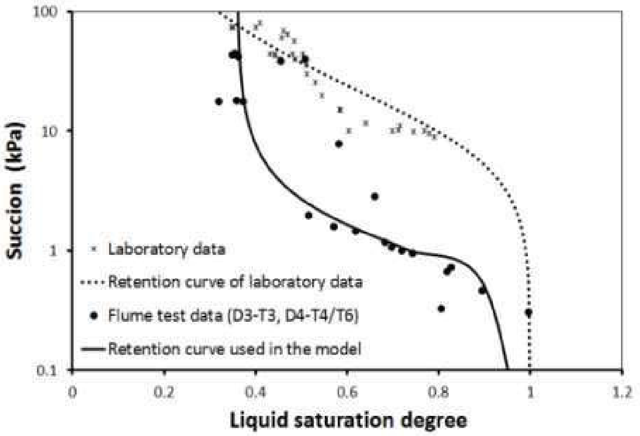

Fig. 2. Retention curve of the material used in the mock-up test.

Table 2. Mechanical parameters of the material used in the mock-up test.

ν	κ	λ	r_{casm}	n	M	r	β	Pc	k
0.3	0.04	0.135	2	2	1.54	0.6	37	$1.\ 10^{-15}$	0

Results from model calibration on test D3 are depicted in Figure 3. Figure 3.a shows a comparison of suction time evolutions at three tensiometers located respectively at the bottom (T3 and T4) and top (T6) of the soil layer. When infiltration starts, tensiometers T6 registered an early and quick decrease in suction, well-reproduced by the model. Tensiometers T3 and T4 respond also with a sharp decrease in suction but delayed for six minutes with respect to T6. This kind of response indicates the advance of a wetting front, well-captured by the model. Figure 3.b shows the comparison between water content profiles computed by the model and measured by TDRs at different times along a vertical profile. Measurements indicate a partial saturation of the upper part of the soil layer during the first 10 mins, followed by the deepening of the infiltration front that reaches layer bottom between 10 and 20 mins. From that time on, saturation increases more rapidly at the bottom than at the top of the sample and water content profiles travel to the right while becoming more vertical. This general pattern is consistent with the front-type advance of hydration evidenced by suction monitoring. After 32 mins, there is a new increase of water content at the top of the sample, of more difficult interpretation. Model captures qualitatively well the hydration pattern and also the quantitative change of water content at the base of soil layer. There are however significant quantitative discrepancies. Particularly, the initial distribution of water content cannot be reproduced by the model, because it lays outside the retention curve identified on Test D4. Model is moreover able to reproduce the amount of final settlements although they appear sooner in the model than in the test (Figure 3.c).

The back-analyzed parameters have been used for the Round Robin test, which consists in predicting the hydro-mechanical response of test C4. According to Table 1, the density of the sample in this test is higher than that of test D3. Permeability and preconsolidation pressure have been consequently corrected according to the Kozeny equation and material virgin compression curve. A value of k=1.76e-5 m/s had been then used for in this test.

Predicted evolution of suction at different depths is shown in Figure 4.a. As a result of the lower permeability, the velocity of the wetting front is lower and the delay between top and bottom tensiometers response is higher than in test D3. Figure 4.b shows the evolution of settlement with time. Model predicts infiltration-induced collapse deformation up to 37 mins. At that time, evolution trends changes and a sudden dilation is predicted in the sample. Two minutes after, program stops converging. The moment of dilation initiation is considered as being the one at which failure takes place, that is 37 mins.

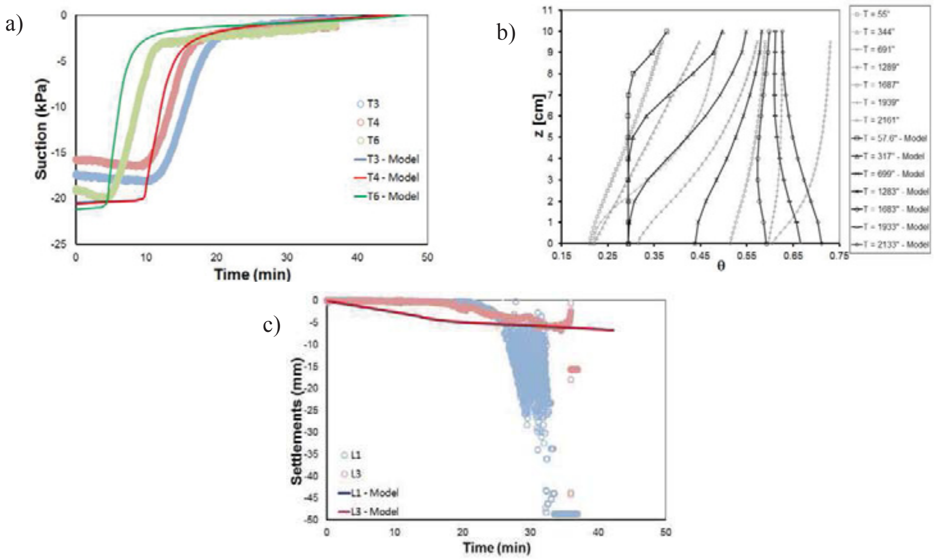

Fig. 3. Small-scale model calibration: a) time evolution of suction at three tensiometers b) Volumetric water content profiles at different times along a vertical profile c) time evolution surface settlement.

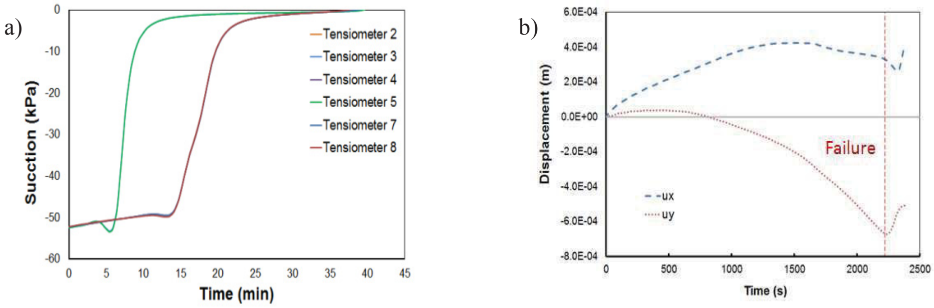

Fig. 4. Small-scale model prediction a) Suction evolution b) Displacement evolution.

3. Field experiment

The field experiment considered in the Round Robin contest is the Cervinara slope, a monitored slope under atmospheric actions located North-East of Naples[8]. Monitored variables include volumetric water content and matric suction at different depths.

For the calibration phase, meteorological data and field measurements were provided from January to August 2011 while the prediction period lasts from the 1st of January to the 12th of February 2012. Meteorological record over the full period is presented in Figure 5. In view of the slope lithology, and only for the sake of the prediction of the hydraulic response, the ground has been simplified into a four-strata column of 4.5 m high (see Figure 6). Phreatic level is imposed at the bottom of the column and a special boundary conditions that captures the main mass and heat fluxes due to ground-atmosphere interactions imposed at the top. Temperature value equal to 10 ºC is initially imposed in all the column and maintained constant during all the computation at its bottom.

The soil-atmosphere boundary condition accounts for several mass and heat fluxes: rainfall precipitation (P), run-off (R), ponding (Po), evapotranspiration (ET), solar short-wave and long-wave radiation (Rn), ground radiation (Rg), ground reflection (Re), sensible heat (Hs) and heat convected by the mass flux (composed essentially by the latent heat released by evapotranspiration). The proper modeling of these boundary fluxes requires a consistent Thermo-Hydro-Mechanical (THM) formulation inside the continuum, able to simulate the coupling processes taking place in soils and rocks under deformations and changes in temperature, liquid and gas pore pressures. The formulation considered is based on the conservation laws of mass, energy and the stress equilibrium, completed by constitutive relationships and thermodynamics restrictions. It is implemented in the Finite Element code Code_bright [1]

The retention curves of the different layers have been estimated on the basis of the relationships drawn by measurements of suction and water content at several depths in the slope. As shown in Figure 7, two water retention curves have been identified: one for slope layers above a depth of 1.5 m, corresponding to the zone of root and pumices ashes, and the second for layers at higher depths, classified as ashes and limestone. Values considered for the intrinsic permeability and porosity are 7 10-5 m/s and 0.7, respectively.

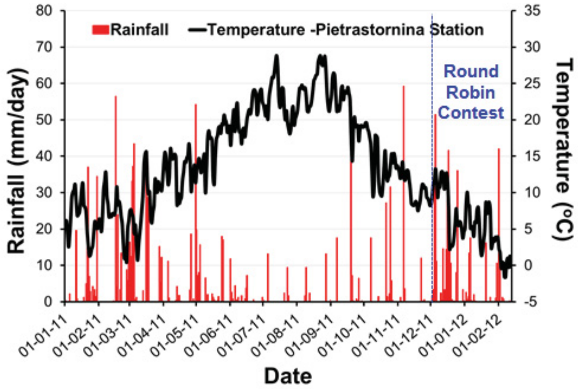

Fig. 5. Atmospheric data record measured at Pietrastornina meteorological station.

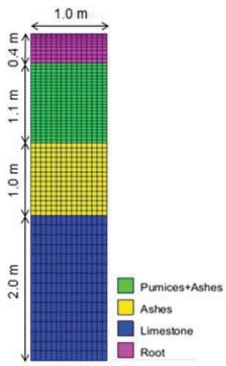

Fig. 6. Geometry and mesh of the large-scale model.

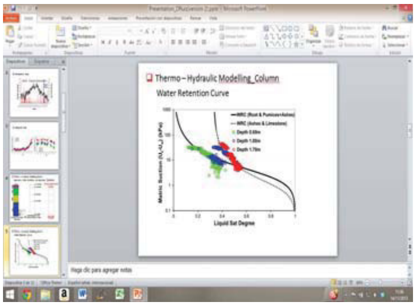

Fig. 7. Water retention curve of the different strata.

The response output by the model is shown in Fig. 8 (time evolution of volumetric water content at 0.3, 0.6, 1.0 and 1.7 m) and Fig. 9 (time evolution of suction at 0.6, 1.00, 1.40 and 1.70 m). From a general point of view, computed volumetric water contents exhibit a very good agreement with measurements at depth 0.6, 1.00 and 1.7 m (except for the last two months) but underestimated them at depth 0.3 m. The latter discrepancy is expected to be due to the fact that the retention curve in the zone of roots is not well-represented by the retention curve considered at 0.6 m. On the other hand, the departure observed for the last two months in Fig. 8c is to be related to the discrepancy existing between the suction-water content relationship measured from January to May 2011 (blue points close to the green ones in Figure 7) and after this period (blue points close to red ones). The causes for such a sudden jump in time of the instrumentation results have to be further investigated. Fig. 9 presents the evolution of liquid pressure at 0.60 m, 1.00 m, 1.40 m and 1.70 m depth. Agreement is good up to end of May 2011 but numerical results start to depart significantly from the measurements after this date. This may be due to the lowering of the phreatic level in the fractured limestone during summer, not represented in the one-dimensional model.

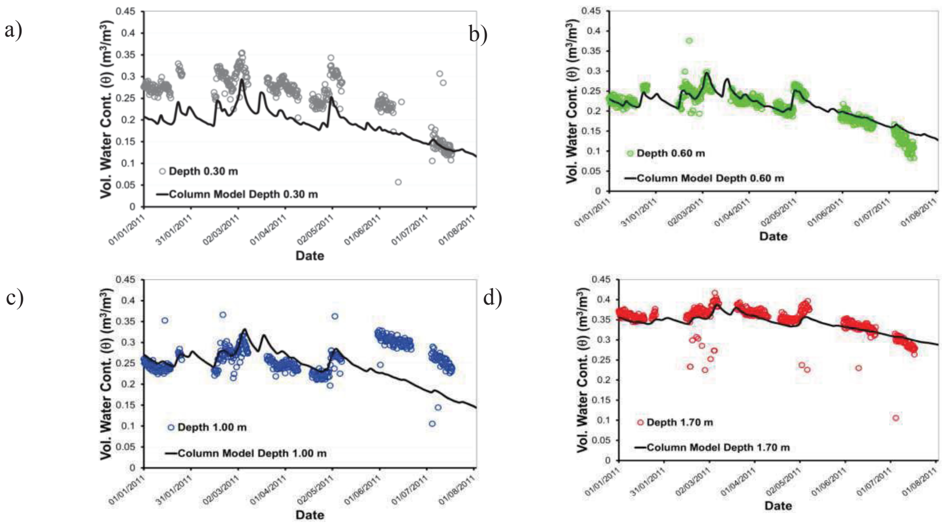

Fig. 8. Large-scale model calibration: comparison of computed and measured volumetric water content at a depth of a) 0.30 m, b) 0.60 m, c) 1.00 m and d) 1.70 m.

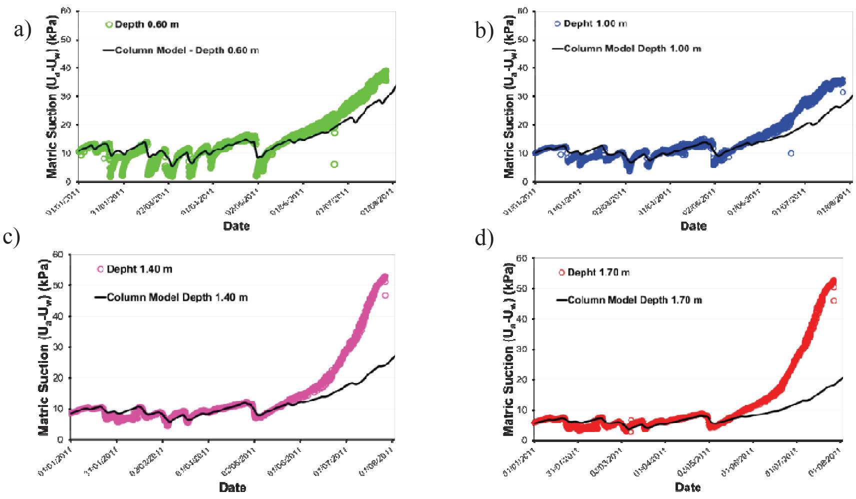

Fig. 9. Large-scale model calibration: comparison of computed and measured suction at a depth of a) 0.30 m, b) 0.60 m, c) 1.00 m and d) 1.70 m.

4. Conclusions

The numerical analyses of the hydro-mechanical response of two slopes in pyroclastic soils has been carried out at two different scales using a thermo-hydro-mechanical Finite Element code that includes a special boundary condition to simulate the ground-atmosphere interactions. The suction dependent mechanical model is based on an adaptation of CASM model for unsaturated soils developed by Gonzalez[6]. The model well predicts the evolution of suction at different depths, surface settlement and time of failure of a mock-up test that simulate the failure of a 40º slope under rainfall. The soil-atmosphere formulation is based on a consistent thermo-hydro-mechanical framework based upon fundamental physics. The model proves to provide good predictions of suction and water content variations in a real slope under meteorological actions.

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