Essential elements for an early warning system to detect flow-slides in pyroclastic deposits

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ABSTRACT: Air-fall pyroclastic deposits on steep slopes in Campania (Southern Italy) are periodically subjected to rainfall-induced landslides that may evolve into catastrophic flowslides. To protect built-up areas, Early Warning Systems (EWSs) were implemented. Existing EWSs are essentially based on pluviometric thresholds or models which are unable to accurately monitor the physical phenomena which are responsible for flow-slide generation in pyroclastic deposits. Over the last 20 years, landslides with no evolution in flow-slide occurred in this area and the alarms generated by existing EWSs in the cases of rainfall were false and very expensive, thus, lowering population trust in EWSs. To improve the existing EWSs, two complex models for pyroclastic soils from Cervinara and Sarno slopes are proposed in the paper, capable of simulating physical phenomena (such as, the saturation increase due to rainwater infiltration, mechanical degradation and undrained instability), control instability phenomena (landslide) and evaluate the post-failure evolution.

1 INTRODUCTION

Several of the upland areas in Campania (southern Italy) are covered by air-fall pyroclastic deposits in primary deposition generally in unsaturated conditions periodically subjected to rainfall-induced landslides that may evolve into catastrophic flow-slides (Olivares & Picarelli 2003; Cascini 2004). The crucial reliability of the forecasts provided by physically-based models used by EWSs for civil protection purposes depends on their ability to reproduce the physical phenomena in question, considering the peculiarity of pyroclastic soil particles and controlling:

a) the instability phenomena (landslides);
b) the post-failure evolution into a flow-type movement (flow-slide).

The availability of experimental observations (from laboratory and in situ investigations, from flume infiltration tests on small-scale slope models (Olivares et al. 2009; Damiano et al. 2012; Olivares et al. 2014)) allows appropriate definition, calibration and validation of physically-based models. Against this background, we analysed two pyroclastic deposits involved in catastrophic flow-slides in Sarno 1998 and Cervinara 1999. Based on the experimental results, for both cases, two "reliable" hydro-geotechnical models are proposed to analyse the slope response of loose unsaturated pyroclastic deposits. These two models constitute the elements to improve existing EWSs.

2 MODELS FOR ANALYSES OF SLOPES INSTABILITY IN UNSATURATED SOILS

In the case of granular shallow deposits, rainfall slope response is a complex hydro-geological and geotechnical process, also for very simple slope geometry and geological structures of subsoil. Each event causing changes in boundary conditions (precipitation, humidity, air pressure, temperature and other weather variables) can induce different slope responses in terms of state of stresses and strains in turn related to the initial state of the soil. For each event, the initial state of slope is a function of the stresses and strain history preceding the event itself. These two brief considerations highlight the absolute necessity to evaluate the slope instability resorting to constitutive models able to properly assess the evolution of stresses and strain for a forecasted rainfall, using as initial condition the data from monitoring and the analyses of slope response history preceding the event.

To this end, hydro-geotechnical models have been widely proposed, in literature, for the analysis of slope response in granular deposits subjected to infiltration. Differently from the last century, when the evolution of slope stability was generally analysed under the hypothesis of fully saturated conditions and of homogeneous and isotropic soil, in recent decades, several more or less simplified infiltration models have been developed to analyse slope response under transient (but uncoupled) unsaturated flow (Fredlund & Rahardjo 1993; Freeze & Charry 1979; Iverson & Reid 1992; Griffiths & Lu 2005). Based on the results of these infiltration models, slope stability analysis can be performed by using simplified approaches that consider the effect of the stress state variable (normal stress and matric suction) on shear strength (Fredlund & Rahardjo 1993), or combine suction and mean net stress in effective stress (Bishop 1959), or approaches where the shear strength changes due to matric suction are directly derived from the soil-water characteristic curve (suction stress-based effective stress SSCC (Lu & Likos 2006)). These simplified infiltration models require a few number of parameters of clear physical meaning to be defined. Although they do not allow to describe all the physical aspects of phenomena they can provide acceptable results in EWSs for very simple slope geometry and geological structure of subsoil if the parameters are experimentally defined and the models are appropriately calibrated.

In parallel, in the last decades, more complex models have been developed that use a fully coupled hydro-mechanical models (Alonso et al. 1995; Lignon et al. 2009; Olivella et al. 1996; Lizárraga et al. 2016). Some of these models should be able to reproduce a large part of physical phenomena that are the basis of slope response in partially saturated soils subjected to infiltration processes even if they require a larger number of parameters to be defined some of which have not a clear physical meaning. They can be used in EWSs, also in complex slope geometry and geological structure of subsoil. But the definition of the parameters requires a development of more complex experimental program and also an in-depth calibration of the model on data from in-situ monitoring (what unfortunately is not always done).

Starting from this excursus, the experimental program presented in the paper tries to answer to the following two questions:

1) Could one of these models be implemented in an EWSs to describe the instability (landslide) of pyroclastic deposits subjected to infiltration?
2) Does the experimental program provide sufficient information to define also the post-failure evolution into a flow-type movement (flow-slide)?

In this respect, we decided to start to create the database for pyroclastic deposits involved in catastrophic flow-slides. The experimental programme already performed on Cervinara ash (Damiano et al. 2012) was also carried out on Sarno ash which was involved in catastrophic flow-slides of 1998.

3 MATERIALS AND METHODS

The two-investigated shallow pyroclastic deposits (Cervinara and Sarno) consist of alternating pumiceous (gravelly-sand) and ash (silty-sand) layers, lying on intensely fractured limestone (bedrock). We mainly focus on the ash layers that, in the stratigraphy, are considered to be responsible for the evolution into flow-slides (Olivares & Damiano 2007).

In both cases, the soils are characterised by surprisingly high porosity (about 70%) and by a relatively low specific unit weight of the soil particle (Gs = 2.6). These properties are typical of a metastable structure responsible for flow-slide generation. In Figure 1, the grain-size distributions of the two ash soils are compared with those indicated by Hunter and Fell (2003) in the case of deposits susceptible to liquefaction under monotonic and cyclic loading. The comparison shows that the grain-size distribution of the soils in question falls within the range of variation of liquefiable deposits.

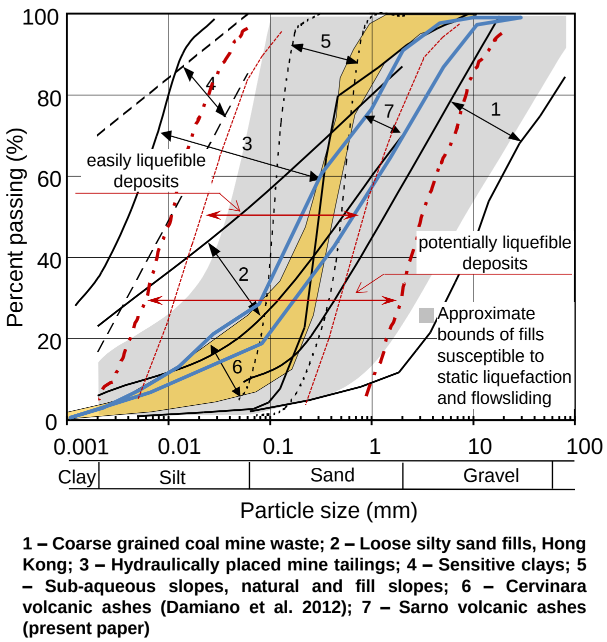

Figure 1. Grain-size distribution of ashy soils compared with other liquefiable soils.

3.1 *The experimental programme*

According to the considerations made above, the experimental programme had the following aims:

1. to define the saturated shear strength;
2. to verify the susceptibility to static liquefaction;
3. to define the role of suction on shear strength;
4. to define the water retention curves and permeability functions.

To achieve such goals, for both deposits, the experimental programme provided saturated triaxial compression tests (TX) and suction-controlled triaxial tests (SCTX). The tests were performed on natural soils with an initial void index ranging between 2.05 and 2.14.

In the case of TX tests, the specimens were directly saturated in the apparatus, applying a wetting stress path characterised by always lower net stress, suction and effective stresses than those acting in situ. This was essential to use the results of TX tests to analyse the potential liquefaction of natural deposits.

To define the water retention curve, data from the tests described below were compared:

- suction-controlled triaxial tests;
- conventional infiltration and drying tests on small-size specimens;
- flume infiltration tests in physical models on large reconstituted specimens.

In the flume infiltration tests, the ash layers were reconstituted by a moist-tamping technique at different porosities. A uniform rainfall ranging between 55–60 mm/h above the ash layer was applied. At different depths and location, suction and water content measurements were performed by means of mini tensiometers and TDR probes.

3.2 *Shear strength (Sr=1)*

Saturated shear strength was measured in drained (CID) and undrained (CIU) triaxial tests on isotropically consolidated natural specimens (Fig. 2). In drained tests, both the materials have a high friction angle (37-38°) and a nil value of cohesion intercept. Such high friction angles are justified in sub-angular shape with sharp edges of pyroclastic particles typical of fall deposits and in the negligible influence of fine components due to low plasticity.

In Figure 2, the undrained stress paths and the drained envelope of strength are reported. A homogeneous response confirms the uniformity detected in physical properties of the two materials. Approaching the failure envelope an undrained instability occurs with a progressive reduction in the shear stress that moves along the steady-state line (or CSL) towards the origin of the axes (static liquefaction). Such undrained instability is also observed for a range of stresses comparable with those acting in situ, confirming a high susceptibility to liquefaction of both the deposits.

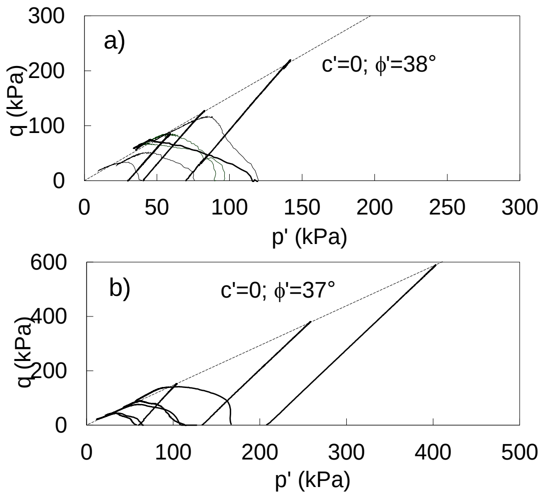

Figure 2. Triaxial test results on natural samples of pyroclastic soils: a) Cervinara; b) Sarno.

With this part of the experimental program the first "ingredients" considered "essential" were identified:

- the properties of these two materials (high porosity and low specific weight) are typical of soils susceptible to liquefaction;
- the grain-size distribution fall right in the middle of the range for potentially liquefiable soils;
- the undrained instability in tests on undisturbed samples in a range of stresses comparable to in situ ones was verified.

In the framework proposed by Olivares and Damiano (2007), after instability, such deposits have a high probability to evolve into a flow-slide if the following conditions are established:

1. water content near saturation at failure;
2. slow rate of excess pore water pressure dissipation compared to the rate of build-up of pore pressure induced by slope movements.

Therefore, to analyse the infiltration processes that lead to failure conditions it is essential to consider constitutive relationships including the effects of partial saturation on shear strength and on hydraulic properties.

3.3 *Shear strength (Sr<1)*

For both sites, the effect of partial saturation on shear strength was defined in SCTX tests on natural samples. In the stress plane, the results for suctions ranging between 10 and 80 kPa and mean net stress between 20 and 80 kPa are reported (Fig. 3a). For comparison, in the same stress plane the two envelopes of saturated shear strength are reported. All the representative unsaturated failure points are localized in the stress plane well above the saturated shear strength envelope, emphasizing the non-negligible role of suction in ashy soils. In Figure 3b, the intercept cohesion is shown as a function of suction ("apparent cohesion"). This result was obtained by assuming shear strength envelopes for partially saturated soils parallel to the saturated envelope and passing through failure points. In both soils, the relationships between cohesion intercept and suction show a strongly non-linear monotonic increase in cohesion intercept. In the case of Cervinara, cohesions slightly greater than 10kPa are obtained by suctions of 70 kPa and 2-6 kPa by suction of 4-8kPa. In the case of Sarno, as for the saturated shear strength, slightly smaller values are reported (intercept cohesion assumes values of 7 kPa for a suction of 50 kPa). These "apparent cohesions" are sufficient to justify the stability of shallow deposits even for suctions very close to zero. Non-linear relationship of this kind can easily be implemented within hydrogeological models capable of describing the evolution of slope stability due to rainfall infiltration.

3.4 *Water retention curves and permeability functions*

The relationships between suction and volumetric water content are analysed in Figure 4 for both the materials. Data on natural samples, from SCTX tests and from conventional laboratory wetting and drying tests, are available. The values at the end of equalization, due to the increments or decrements of suction, in SCTX tests (68 mm of diameter), or of water content, in wetting and drying tests (dx = dy = dz = 10 cm), are reported. Experimental points have been obtained by coupling suction with gravimetric water content.

Both the materials show comparable trends and allow a quantitative description of the functional relationship (van Genuchten (1) in Fig. 4) for suctions greater than 7-10 kPa.

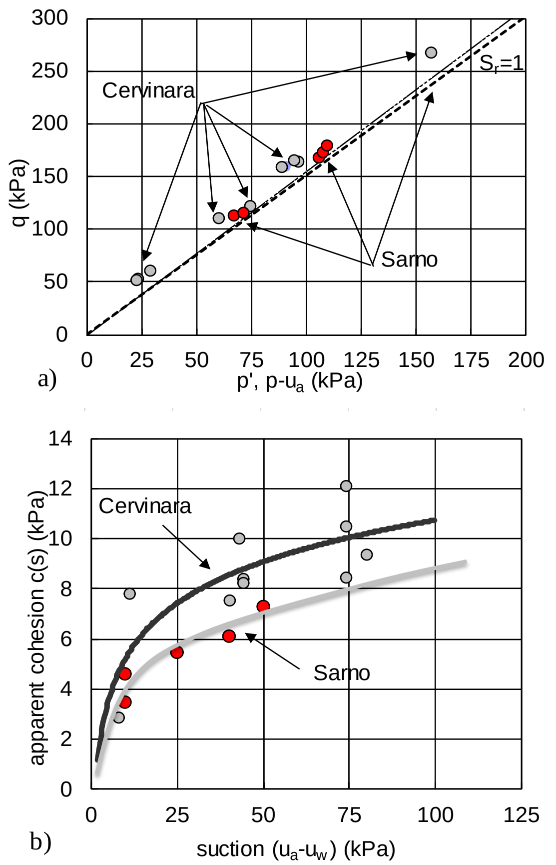

Figure 3. Shear strength: a) stress plane; b) intercept of cohesion as a function of suction.

To investigate the SWRC close to saturation, other data series have been retrieved from infiltration tests on small-scale model slopes. In this case, reconstituted soil deposits (l=140 cm; b=50cm; h=10 cm; α=38°) (with a porosity ranging between 69% and 76%) have been subjected to artificial rainfall ranging between 40 mm/h and 80 mm/h till their complete saturation. Experimental points have been obtained by coupling water content measurements from TDR probes and suction measurements from "small tip" tensiometers installed close to each other. All the data are reported in Figure 4. It can be noticed that the experimental points seem to cluster along a different curve which have been fitted by van Genuchten (2) in the Figure 4.

In the case of triaxial and conventional wetting and drying tests, changes of suction or of water content have been imposed for long times of equalization, up to reach an equilibrium condition. In the case of flume tests, we analyse in a point, the evolution of suction and water content during the transient regime induced by infiltration. Moreover, different size of specimens, different boundary conditions may well explain the differences between the two set of data (relations 1 and 2 in figure; Damiano & Olivares 2010). We consider more reliable the relationship (2) to reproduce the on-site SWRC as it has been obtained for boundary conditions closer to real slope conditions. In fact, Cervinara data from monitoring (light blue points in Fig. 4a) are closer to relationship (2).

In any case, the relationships describe a typical granular soil response with a low air entry pressure and wide transition zone, confirming for both soils the similarities already found for the other mechanical properties.

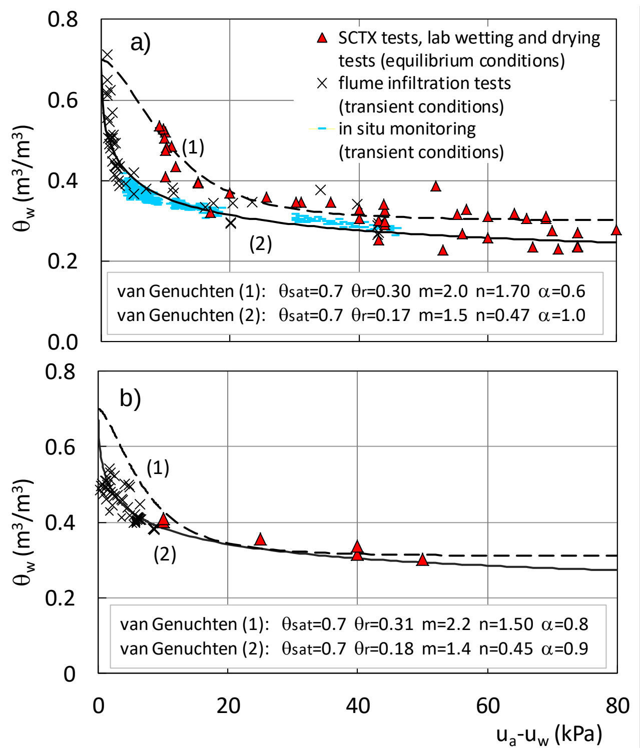

Figure 4. (a) Cervinara and (b) Sarno: water retention curves from SCTX tests, infiltration tests in a small-scale slope model and in situ monitoring.

The permeability functions (last "ingredients") are analysed in Figure 5. In the same SCTX tests, hydraulic conductivity was determined by the expression proposed by Kunze et al. (1968), analysing the transient regimes induced for each increment of suction. For the sake of comparison, in the same figure, the values of the Brooks and Corey relationship (1964) or the Gardner relationship (1958) are proposed. That said, starting from the saturated hydraulic conductivity (about 10^{-6} m/s), there is a strong reduction up to 10^{-8} m/s (for suctions of 50-80kPa). The results for Cervinara and Sarno are in practice comparable, providing quantitative functional relationships which may be easily implemented in a soil model.

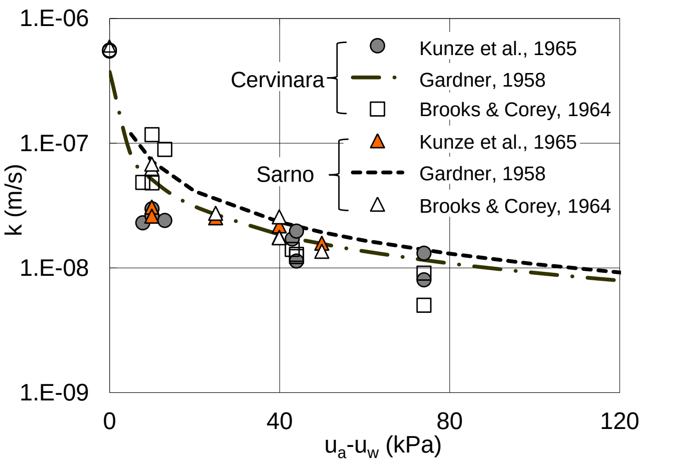

Figure 5. Permeability functions in SCTX tests: suction equalization phases in isotropic compression tests

4 THE SOCIOECONOMIC VALUE OF EARLY WARNING SYSTEMS

Rainfall-induced landslides and even false alarms of such catastrophic events produce adverse technological and productivity shocks, reducing present and future values of investments. This makes the development of effective EWSs a very important ex-ante solution to help local economic development.

In the Dixit and Pyndick (1994) and Hull (2012) framework of real options, an effective EWS is a tool to embed the value of 'temporary abandonment options' in projects; moreover, it highlights long 'periods of peace', increasing the net value of projects due to the embedded 'options to expand' and 'extend'. Correct evaluation of the natural hazard risks will help management to increase productive capacity, the scale of a project's operation, to extend the life of the assets without hesitation during any positive phases of their business cycle and at lower costs (e.g. lower insurance premiums and higher economies of scale). In contrast, the EWS could inform management promptly of the advisability to reduce the scale of their operations by embedding a 'contraction option' to the value.

But, existing EWSs are not effective and - worse case is- these may trigger false alarms and hence the dreaded negative technological and productivity shocks. This happens essentially because the true nature of the soils is not considered and remains confined in a 'black box'. Moreover, the triggering thresholds are only defined based on a time series of rainfall events and of extremely simplified analysis of infiltration processes and of stability conditions of slopes (i.e. only in saturated conditions).

The study of the response of non-saturated soils would allow better characterization of the triggering mechanisms of landslides induced by extreme meteorological events and lead to a less uncertain environment in which researchers could formulate their expectations (beliefs and priors) to implement correct calibration and support decisions.

The reliability and benefit of an EWS strictly depends on adopting realistic hydro-geotechnical models (e.g. for unsaturated soils) that enable researchers to detect the right triggering thresholds and minimize the risk of false or late alarms for a better evaluation of the true value at risk.

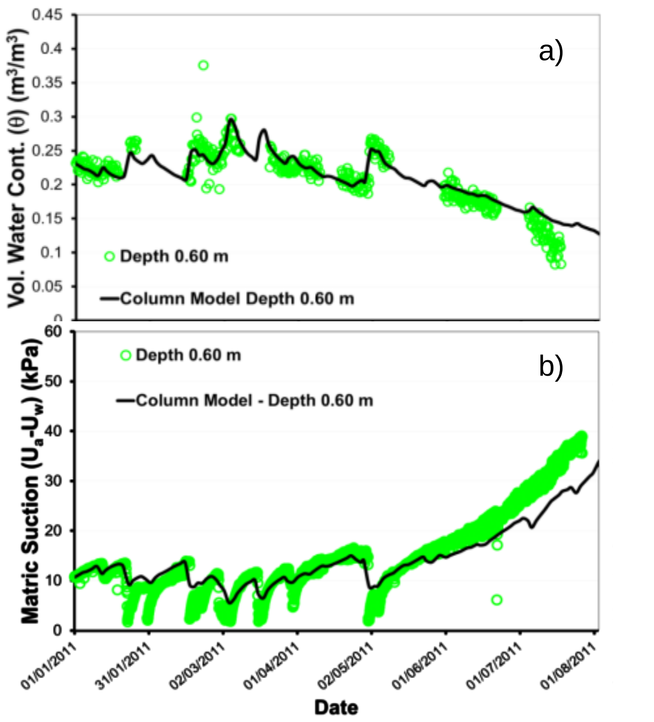

Figure 6. The Round Robin Test: comparison of computed and measured volumetric water content (a) and suction (b) at a depth of 0.60 m.

5 CONCLUSIONS

The occurrence, but also of the false alarms, of rainfall-induced catastrophic flow-slides produce technology and productivity shocks, compromising the value of future and current investments in these areas at risk. Considering all the elements defined in this paper as "essential ingredients" for hydro-geotechnical models will allow improvements in existing EWSs; considering the nature of pyroclastic soils and the effects of partial saturation conditions on shear strength will improve the ability to predict slope response to rainwater infiltration and hence the predictive capability of the EWSs with a clear and persistent advantage in terms of reducing the risk of false or late alarms.

With this aim, in 2013 during the third edition of the Italian Workshop on Landslides (3rd IWL), a session was dedicated to a Round Robin test on landslide hydrological modelling (Bogaard et al. 2014). The participants from several European universities were provided with the "essential ingredients" to simulate both the experiments carried out in a small-scale model slope and the response of the

Cervinara slope to a measured precipitation event. The participants were asked to calibrate their models based on the data provided and were challenged to simulate the results of the infiltration tests and slope response to assigned records of precipitation and temperature data. The best agreement was obtained by Villarraga et al. (2014) who used a fully coupled thermo-hydro-mechanical model implemented in the finite element code Code_Bright (Olivella et al. 1996). The results are reported in Figure 6 in terms of comparison between the measured and the simulated water content (Fig. 6a) and suction trends (Fig. 6b) at the depth of 0.6 m in the Cervinara slope during eight months of measurements which show that the model, calibrated on the basis of the "ingredients" provided, is able to capture slope response. However, also simpler models such as those used by Ahmadi-Adli et al. (2014) and Farulla and Rosone (2014), do not consider a fully coupled hydro-mechanical approach and were able to follow slope response to meteorological input, showing that, in the presence of good quality data, reliable predictions are possible.

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