Stability Analysis of Pyroclastic Covers by a new Geoelectrical-Hydrogeological Approach

ROSA DI MAIO[1], ESTER PIEGARI[1] and SOLANGE SCOGNAMIGLIO[1]

[1] Department of Earth Sciences, University of Naples "Federico II", Italy, Largo San Marcellino 10 - 80138 Naples (Italy).

rodimaio@unina.it

Abstract

Debris-flows hazard is strictly correlated to the water content of loose deposits mantling a slope. Obviously, many other factors predispose and influence a slope to landsliding (such as the slope morphology, the geological setting, the soil thickness, etc.), but in most cases a water content variation is the most frequent triggering factor of debris-flows. Thus, it would be helpful to define water content thresholds, which may be critical for debris-flow mobilization.

In this framework, we propose geoelectrical measurements as an important tool for seepage analysis and landslide hazard assessment. By means of in-situ resistivity tomography surveys, we define the stratigraphical setting, which is needed to create a synthetic slope model. By means of laboratory resistivity measurements, we link electrical resistivity to the percentage of water content in order to obtain the water content distribution within the surveyed slope in a specific period of the hydrological year. Such a distribution is used to validate the synthetic water content distribution resulting from steady-state seepage analysis, which is realized by using geotechnical parameters. Next, we perform a transient-state seepage analysis by imposing to the achieved synthetic water content distribution the daily rain rate of the rainfall occurred before a catastrophic landslide event of the past. Transient analysis provides the critical water content distribution of the surveyed cover for the considered debris-flow event. Finally, by converting critical water content in resistivity values, we obtain information about the stability condition of the surveyed slope by calculating the previously introduced geophysical safety factor, defined in terms of slope angle and resistivity.

An application of the proposed tool in a test area located on the Sarno Mountains (Campania region, southern Italy) is presented. The main finding of the shown example is the identification of saturated conditions of the shallowest pyroclastic layer of the cover on the day when a calamitous landslide event occurred.

Introduction

Peri-Vesuvian area encloses a portion of the Campania region (southern Italy) characterized by ash-fall deposits resulting from the volcanic activity of the Mt. Somma-Vesuvius, which overlap a carbonate basement. Geological, structural and hydrogeological conditions of this area may often trigger very rapid landslides as debris-slides and debris-flows.

Many authors currently study how to evaluate the water content of such loose deposits and its variations over time. In particular, due to the well-known dependence of the soil matric suction from the water content, most of recent researches (e.g., CASCINI and SORBINO, 2004) are focused on monitoring the soil suction values at various depth from the slope surface. These values are used to realize a synthetic suction (or equivalently water content) model of the slope

(SORBINO, 2005) and to get information about its hydrological status. However, suction measurements give local information about soil condition around porous probes and down to a depth of 3 m at most.

Alternatively, we propose an innovative tool for groundwater seepage analysis substantially founded on laboratory and in-situ geoelectrical measurements, whose aim is the definition of effective early warning thresholds for debris-flow landslide initiation. The main advantages of our proposal are: the non-invasiveness of the measurement technique and the possibility to take into account the local changes of soil properties on considerable volumes by means resistivity tomography surveys, which in turn provide the water content distribution within the whole surveyed volumes.

In order to verify the potentiality of the proposed tool, we present an application in a test area of the Campania region (southern Italy), where debris-flow phenomena of pyroclastic soils are very often induced by critical rainfall events.

A combined geoelectrical-hydrogeological approach

Figure 1 shows a schematic diagram of the proposed geoelectrical-hydrogeological approach. We use the results of high-resolution 2D resistivity tomographies (*ERT*) to obtain a stratigraphical model of the slope and the results of geotechnical measurements to define the hydraulic behavior of the pyroclastic cover. Once we have realized a synthetic slope model, a steady-state representative of in-situ soil conditions is achieved by using a *trial and error* approach. This consists in comparing the synthetic water content distribution within the cover, resulting from seepage analysis, with that resulting from a joint interpretation of the in-situ and laboratory resistivity measurements (DI MAIO and PIEGARI, 2011). Next, we use rainfall data of real storms to simulate the in-situ condition preceding a catastrophic past landslide event occurred close to the survey area. The applied conditions provide the 2D critical water content distribution within the investigated cover on the day when the landslide occurred.

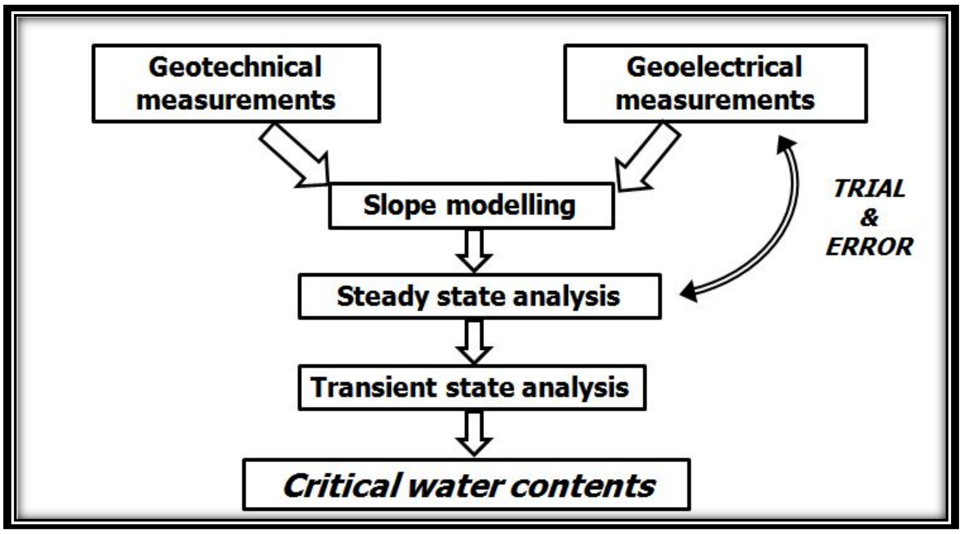

Fig. 1: Schematic diagram of the proposed geoelectrical-hydrogeological approach.

Application to the Sarno landslide event of May 5, 1998

The proposed approach has been implemented on a test area localized on the S-W slope of Mts. Sarno (Campania region, southern Italy). These mountains are covered by ash-fall deposits characterized by pumice and ashy layers, resulting from the volcanic activity of the Mt. Somma-Vesuvius, which overlap a carbonate basement. Such deposits may be occasionally mobilized from the slope and produce huge and very rapid rainfall-induced debris flows, which may cause significant property damage and loss of human life in the tows located at the foothill of the slopes. The most serious event occurred on May 5th, 1998, when severe rainfall-triggered landslides devastated the cities located at the foothill of Mt. Pizzo D'Alvano, causing more than 150 casualties. The test area is localized upstream the initial detachment area of two landslides occurred on May '98 (Figure 2).

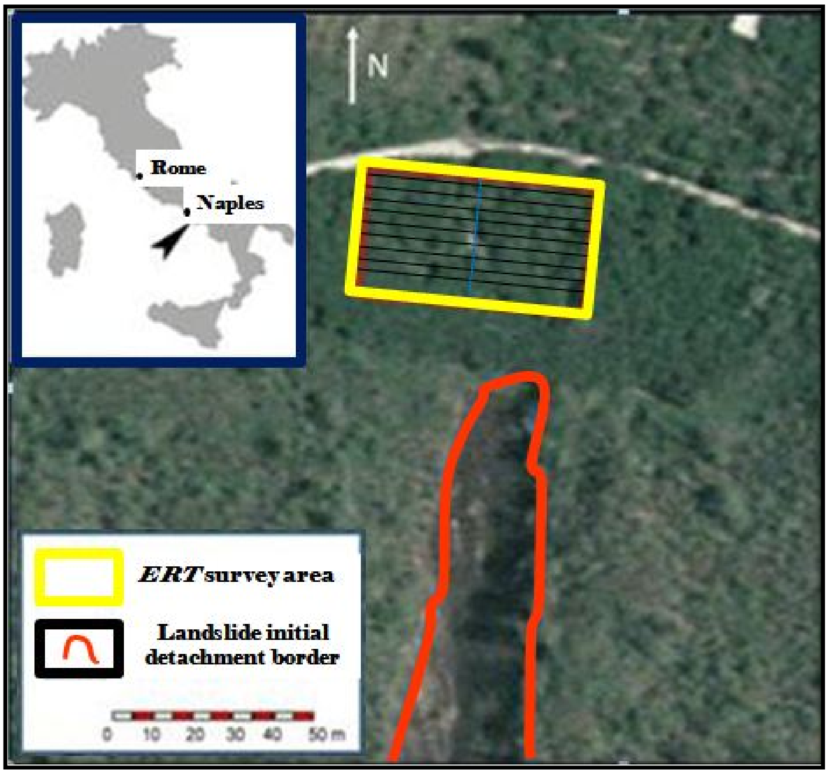

Fig. 2: Map showing the location of the survey area. Black lines indicate the 2D resistivity profiles; blue line specifies the orientation of the synthetic slope model.

In the test area, we performed 2D resistivity tomography surveys along 9 W-E profiles (black lines in Figure 2), 58 meters long and 4 meters spaced, by using a Wenner-Schlumberger array (DI MAIO and PIEGARI*,* 2011). As an example, figure 3a shows the resistivity section obtained along one of the investigated profiles. Looking at the figure, the cover appears sketchily described by a shallow resistive layer overlapping a wide conductive layer; both deposits may be ascribed to pyroclastic materials. Conversely, the deepest resistive layer that emerges at about 5 m below ground level (b.g.l.) is likely correlated to the limestone bedrock. The geoelectrical measurements were carried out both in the autumnal and spring season and, by using the 3D data inversion algorithm of LOKE and BARKER (1996), 3D resistivity distributions within the pyroclastic cover were obtained.

By comparing geoelectrical and geotechnical laboratory measurements performed on pyroclastic samples collected in the test area, a more detailed stratigraphy of the surveyed area was attained (Figure 3a). Such a stratigraphical setting was used to realize the synthetic slope model, approximately N-S oriented (blue line in Figure 2), which is required for the seepage analysis. The slope modelling was based on two main steps: the first consists on the discretization of the slope by using a finite element mesh and the second one consists on assign the hydraulic properties to each layer characterizing the pyroclastic cover. About the first step, the synthetic stratigraphical model is illustrated in Figure 3b. The thickness of each layer was obtained from the results of the high-resolution 2D resistivity surveys previously mentioned. In particular, 7 regions were defined, 6 for each layer of the pyroclastic cover and one for the limestone bedrock. To characterize the hydraulic behavior of pumice and ashy layers, we used two different types of curves retrieved from literature geotechnical data: hydraulic conductivity vs. suction (Cascini et al., 2000) and suction vs. water content (i.e., retention curves) (Sorbino, 2005; De Vita et al., 2012).

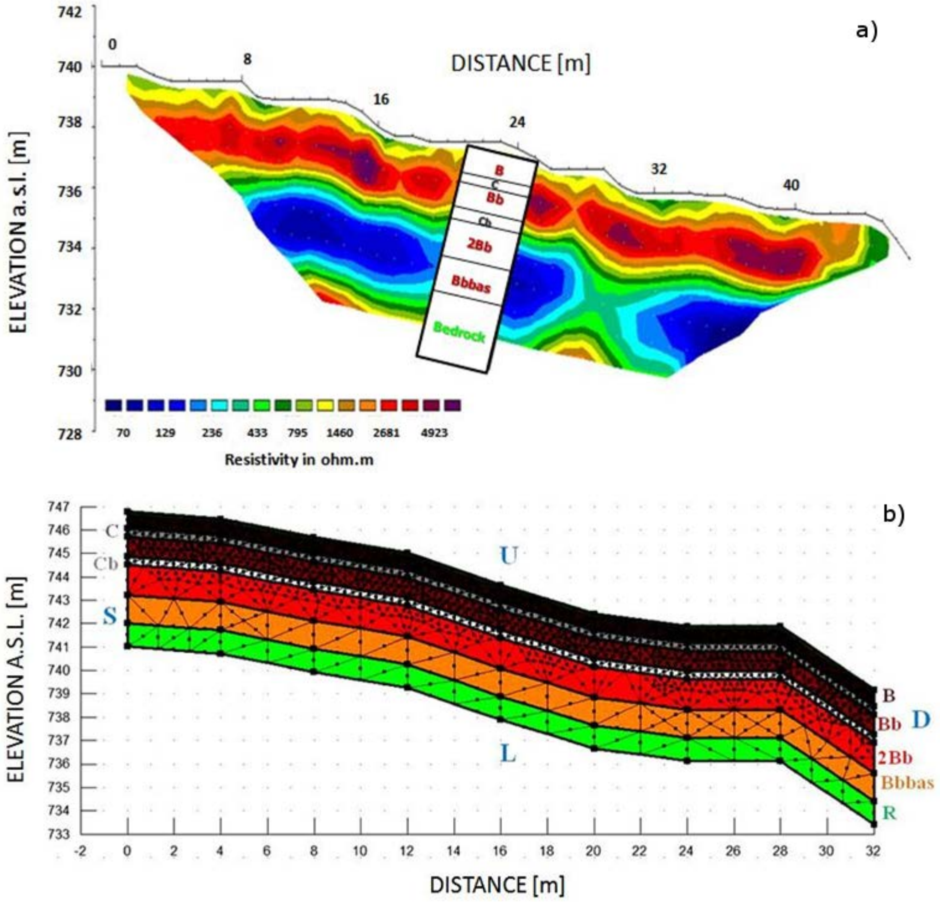

Fig. 3: a) An example of resistivity section obtained along one of the 9 investigated ERT profile. The superimposed stratigraphic column indicates the layers of the cover that overlaps the bedrock R (after Di Maio and Piegari, 2011). b) Slope model used to perform seepage analyses. The 7 regions represent the 6 layers of the surveyed pyroclastic cover and the limestone bedrock. On the left and right sides of the model is indicated the name of each layer, while the blue letters designate the upper (U), lower (L), right (D) and left (S) edges of the model.

Steady-state seepage analysis

Steady-state analysis is aimed at providing in-situ soil condition of the investigated cover in a specific period of the hydrological year. To achieve it, we propose to apply a *trial and error* routine based on geoelectrical measurements. First, we assign to the top of the slope model a steady (over time) rain rate. As result of the steady-state seepage analysis, we obtain a synthetic 2D water content map within the pyroclastic cover. Subsequently, such synthetic water content values are compared with the water content distribution resulting from laboratory geoelectrical characteristic curves (De Vita et al., 2012), which link resistivity values to the corresponding water content. If there is a good agreement between the two distributions, then the synthetic 2D water content map resulting in output from steady-state analysis is really representative of in-situ conditions. Otherwise, it is necessary to re-iterate the routine by applying a different input unit flux at each iteration until a good agreement is found. To perform the steady-state analysis, we considered the top, bottom and right borders of the model as open edges. This means that water can pass through them, while the left edge is closed to ensure that water exits from the system only through the bottom and the right edge.

It is worthwhile noticing that geoelectrical measurements are used as innovative and effective tool in seepage analysis, since they validate the steady-state representative of in-situ soil conditions.

Transient-state seepage analysis

Transient-state analysis is aimed to simulate soil conditions on the day of a specific landslide event and then to define water contents that might be critical for the stability of the surveyed pyroclastic cover.

In detail, as transient boundary conditions, we applied to the spring steady-state of the investigated area the daily rain rates of the rainfalls occurred before the ’98 landslide event. The resulting synthetic water content map showed highest water content values in the ashy layers and downstream the model, thus indicating this part of the slope as mainly susceptible to debris-flow phenomena. To perform a more detailed analysis, we plotted for each one of the 6 pyroclastic layers the water content vs. time (Figure 4). For shallow ashy layer the water content trend over time follows the rain rate trend, while the deepest layers reach maximum water contents gradually over time and slower than *B* layer. The shallowest layer (*B*) has a water content value of about 46% on the day when the landslide event occurred. This means that the *B* layer was in a saturated condition as deduced by the resistivity laboratory analyses. Moreover, the water content peak of this layer corresponds to the day when landslide occurred. So, we can suppose that the slope stability was affected by the water content of both the shallower and the deeper layers; but most likely, the landslide triggering was caused by the water content of the shallowest layer.

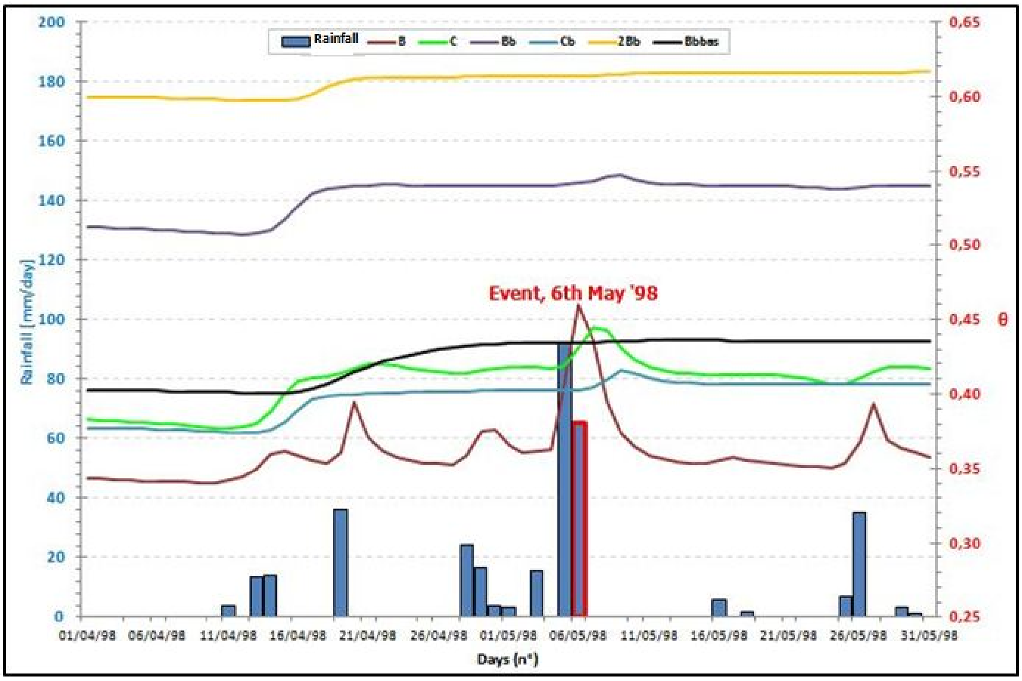

Fig. 4: Water content (θ) vs. time for each layer of the pyroclastic cover. The curves are correlated with the daily rainfall histograms (blue rectangles). The rectangle marked with the red edge indicates the rainfall occurred on May 6th, 1998.

Finally, to assess the stability condition of the surveyed slope we use the geophysical safety factor (FS) previously introduced by PIEGARI et al. (2009) in terms of resistivity values and slope angles. The *FS* map of the test area was calculated by using resistivity values at a depth of 70 cm b.g.l. (corresponding to the thickness of the *B* layer). The *FS* values are found everywhere greater than 1. This means that the slope during the spring season is stable. Converting the critical water contents values, resulting from the transient seepage analysis, into resistivity values by using the characteristic electrical curves of the upper ashy layer (DE VITA et al., 2012), we evaluate the FS distribution at the same depth b.g.l. on the day when the considered landslide event occurred. As expected, FS values are still greater than 1 (Figure 5) for the investigated area of figure 2, which was not involved in the landslide event. Interestingly, by calculating FS with a rigid shift downstream, within initial detachment area, its values (that here we do not show for brevity) are found lower than one, confirming that the downstream part of the slope was effectively unstable on the day of the considered past landslide event.

Anyway, it is worth to underline that looking at the map of Figure 5 it is possible to recognize an elongated strip, approximately N-S oriented, where FS values are lower than surrounding. This area might be associated to a structurally weak sector of the investigated slope. In fact, we have observed that the elongated strip is at the centre of the initial detachment area of the considered landslide event, which is located downstream of our survey area (Figure 5). So we can hypothesize that such a buried structural weakness might be related to the landslide trigger zone that extends upstream the initial detachment area.

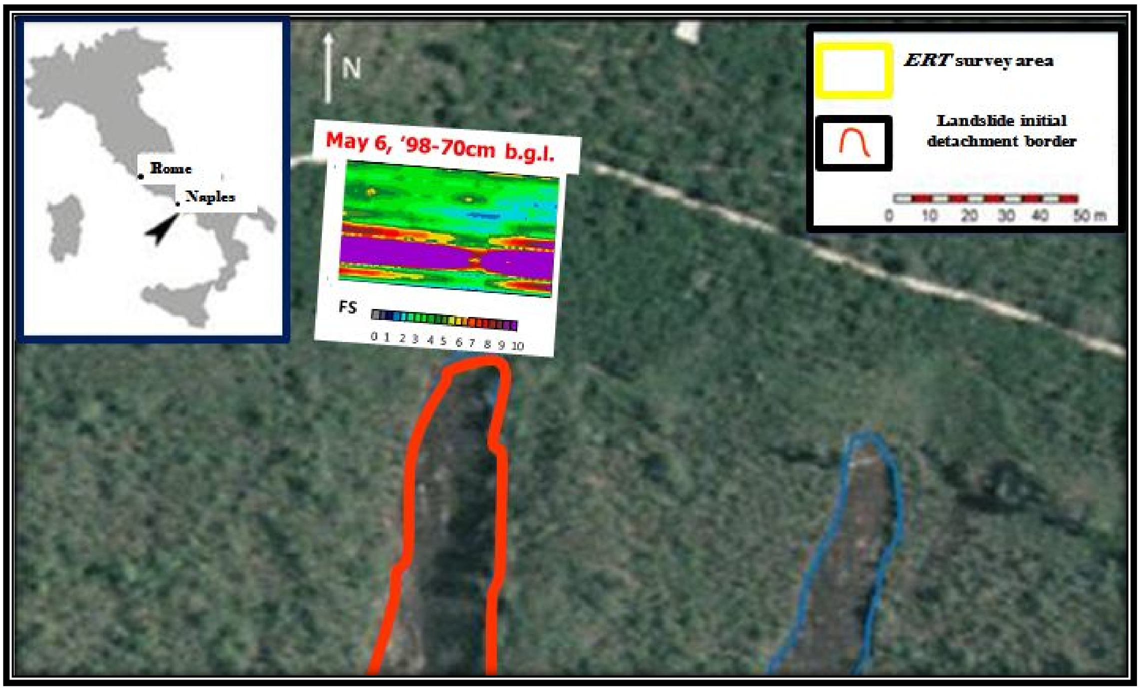

Fig. 5: Geophysical FS map of the survey area on May 5th, 1998, when the considered debris-flow event occurred. The FS values refer to a depth of 70 cm b.g.l. Note that the elongated strip characterized by FS values lower than surrounding is at the center of the initial detachment area marked with the red line.

Conclusions

A new geoelectrical-hydrogeological approach has been developed to estimate the water content distribution within pyroclastic covers, which could be critical for the stability condition of the investigated slopes. The proposed approach has been applied to a test area on Sarno Mountains, where intense rainfall events periodically trigger landslides. The analysis has identified a saturated condition of the shallow layer and a quasi-saturated condition for the deepest layers on the day when a landslide occurred. These results encourage studying critical conditions of any other slope mantled by loose deposits and hence subjected to debris-flow mobilization. We point out that the proposed approach could be a useful tool to both monitor the evolution over time of the water content distribution within loose deposits and determine alarm water content thresholds for each considered slope in support of short-term landslide forecast.

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