Slope-atmosphere interaction in a tectonized clayey slope: a case study

Federica Cotecchia,* Giuseppe Pedone,* Osvaldo Bottiglieri,* Francesca Santaloia,** Claudia Vitone*

Summary
Rainfall infiltration to depth in slopes formed by clayey soils has been generally considered minor, to the extent of being assumed not influential on deep instabilities. As a consequence, rarely monitoring campaigns include piezometric monitoring at large depths. Furthermore, the modelling of seepage at depth is generally not satisfactory because it has to account for the lithostratigraphy of the whole slope and the hydro-geological boundary conditions, seldom surveyed with the appropriate accuracy.

The present paper addresses this gap of knowledge in the field of slope-atmosphere interaction, being concerned with the effects of climate on the equilibrium at large depths in slopes formed by clayey soils. In particular, the clayey soils of reference are very widespread in the southern Apennines (Italy), often part of tectonized turbidites, that are in general sequences of fissured clays and fractured rock strata.

The paper discusses the results of a research on a case history, the Pisciolo hill-slope (Melfi, Italy), a pilot site largely representative of the slopes in the Daunia and Lucanian Apennines. In the slopes of this region the combination of the clay poor strength properties with the high pore-water pressures prompts the propagation of deep failures, resulting in slow to extremely slow landsliding in slopes of even small inclination.

Therefore, the research is aimed to investigate the sources of the large piezometric heads that predispose the slope to instability and the external causes that trigger the slope accelerations. The geological model of the Pisciolo slope and the results of the mechanical and hydraulic characterization of the fissured clays are first presented in the paper. Thereafter, numerical analyses of the seasonal rainfall infiltration and evapo-transpiration are reported with the aim to predict transient flow conditions and to verify the agreement with field monitoring data.

1. Introduction

In recent years the scientific literature has been reporting significant research developments in the field of soil response under climatic actions and the related interaction of slopes with the atmosphere [CASCINI et al., 2010; CASCINI et al., 2011; SMETHURST et al., 2012; TOMMASI et al., 2013]. This interaction influences the stress-strain conditions across the slope and the slope stability. In particular, the climatic variables: rainfall, temperature, sun radiations, wind and relative humidity, determine alternatively the inlet flow and the outflow at the slope top boundary, that in turn produce variations of the state of the soils at the ground surface in terms of: void ratio, e, suction or positive pore water pressure, s and u respectively, degree of saturation, Sr, and hence, the distribution of the pore water pressures in the seepage domain below.

The advanced modelling of the slope-atmosphere interaction requires a thorough assessment of both the geo-mechanical and the hydraulic slope features, introduced as slope factors by Terzaghi in 1950, since the behaviour of the slope in relation to climate is the result of hydro-mechanical coupled processes [NYAMBAYO et al., 2004]. Indeed, the relation between slope deformations and climatic events can be interpreted only through the acknowledgment of the slope geo-structural set-up, soil stress-strain behaviour, hydraulic properties and boundary conditions. Also appropriate uncoupled analyses of the transient seepage through the slope relating to climate have to implement thorough simulations of the slope lithostratigraphy and of the hydraulic properties of the lithotypes and, based on the results of such analyses, a first instance assessment of the slope mechanical response and stability is possible in the light of the mechanical behaviour of the slope soils.

Nowadays, the slope-atmosphere interaction modelling benefits from the increased knowledge about the hydraulic and the mechanical behaviour of partially saturated soils. In particular, it is now possible to model the retention properties of natural soils, traditionally formalized by the soil water retention curve, WRC, accounting for the influence of both the geo-mechanical and the hydraulic slope features, introduced as slope factors by Terzaghi in 1950, since the behaviour of the slope in relation to climate is the result of hydro-mechanical coupled processes [NYAMBAYO et al., 2004]. Indeed, the relation between slope deformations and climatic events can be interpreted only through the acknowledgment of the slope geo-structural set-up, soil stress-strain behaviour, hydraulic properties and boundary conditions. Also appropriate uncoupled analyses of the transient seepage through the slope relating to climate have to implement thorough simulations of the slope lithostratigraphy and of the hydraulic properties of the lithotypes and, based on the results of such analyses, a first instance assessment of the slope mechanical response and stability is possible in the light of the mechanical behaviour of the slope soils.

Nowadays, the slope-atmosphere interaction modelling benefits from the increased knowledge about the hydraulic and the mechanical behaviour of partially saturated soils. In particular, it is now possible to model the retention properties of natural soils, traditionally formalized by the soil water retention curve, WRC, accounting for the influence...
of the soil composition, state and structure [Fredlund and Rahardjo, 1993; Leong and Rahardjo, 1997; Gallipoli et al., 2003; Tsampousoi et al., 2013a], and the hydraulic conductivity, $k$, as function not only of the soil porosity, $n$, but also of the degree of saturation, or, alternatively, of the soil matric suction. At the same time, several constitutive models of the soil mechanical behaviour under partial saturation conditions have been developed [Alonso et al., 1990; Wheeler and Sivakumar, 1995; Laloui et al., 2003; Tsampousoi et al., 2013b]. Conversely, more limited remains the database characterizing the weather variables required for advanced modelling of slope-atmosphere interaction, a need that has only recently been prompting appropriate local climate monitoring at several sites. This lack of data still forces for physically based semi-empirical estimates of the evaporation and evapo-transpiration on slopes [Allen et al., 1998].

Most of the published modelling of slope-atmosphere interaction has so far concerned slopes location of shallow failures, mostly generating soil slipping, earth flowing, or flow-sliding [Cruden and Varnes, 1996; Picarelli et al., 2003]. These landslide mechanisms are mostly controlled by the geo-hydro-mechanical factors [Terzaghi, 1950; Cotecechia et al., 2011] occurring within shallow depths and they are generally triggered by single rainfall events of given duration and intensity, depending on the slope-climate interaction preceding the events. The direct connection of the slope failure to the rainfall infiltration during the single rainfall event has led to identify rainfall duration and intensity as threshold variables for these types of landslide mechanisms. The location of failure mostly within the soils that change in saturation degree during the rainfall event, has emphasized the need for fully coupled modelling of the hydro-mechanical processes bringing about failure [e.g. Gomezna et al., 2007]. Conversely, very limited is the literature concerning the effects of climate on the equilibrium conditions at large depths in slopes, where soils are saturated, and this is the case especially for clay slopes [Alonso et al., 2003; Cascini et al., 2010; Tommasi et al., 2013].

Rainfall infiltration to depth in slopes formed by clayey soils has been generally considered minor, to the extent of being assumed not influential on deep instabilities. As a consequence, rarely monitoring campaigns include piezometric monitoring at large depths. Furthermore, the modelling of seepage at depth is generally not satisfactory because, although mostly addressing saturated soils, it has to account for the lithostratigraphy of the whole slope and for the hydro-geological boundary conditions, seldom surveyed with the appropriate accuracy. The present paper addresses this gap of knowledge in the field of slope-atmosphere interaction, being concerned with the effects of climate on the equilibrium at large depths in slopes formed by clayey soils. In particular, the clayey soils of reference are those typically present in the Southern Apennines (Italy), often part of tectonized turbidites, that are sequences of clays and rock strata. Due to intense tectonic deformation processes, the clays are generally fissured and the rock strata are fractured and float as disarranged inclusions in the clay mass [Santalio et al., 2001; Cotecchia et al., 2006; Cotecchia et al., 2010; Cotecchia et al., 2012]. The acknowledgement of these lit stratigraphic and macro to meso-structural features of the slopes will be shown to be crucial for the interpretation of the piezometric conditions.

Extensive research on the mechanics of the saturated fissured clays part of these turbidites has been developed in the last decades [Cotecchia and Santalio, 2003; d’Onofrio et al., 2009; Vitone et al., 2009; Vitone and Cotecchia, 2011; Vitone et al., 2013a; Vitone et al., 2013b]. The results have given evidence to the peculiarly low strength of these clays, found to be even weaker than the same clay when reconstituted in the laboratory. As a consequence, the strength properties of these clays are a fundamental predisposing factor to landsliding in the geological context of reference. Conversely, the hydraulic characterization of these clays is very recent and is one of the original issues dealt with in the present paper.

The paper discusses the interaction with the atmosphere of slopes in clayey turbidites through the results of an experimental research on a case history, the Pisciolo hill-slope [Fig. 1; Cotecchia et al., 2012], a pilot site largely representative of the slopes in the Daunia and Lucanian Apennines. This portion of the Apennine chain occurs at the eastern margin of the chain, just west of the subduc-
tion contact located in the Apennine fore-deep, as shown in figure 2. In the slopes of this region the water table is generally shallow and piezometric monitoring has provided evidence of recurrent very high piezometric heads down to large depths [even 50 to 80 m depth; COTECCHIA et al., 2012; PEDONE et al., 2013]. Therefore, the seepage conditions in the slopes represent another crucial predisposing factor to landsliding [COTECCHIA et al., 2009; COTECCHIA et al., 2011]. Indeed, in the region, the combination of the poor strength properties of the clays with the high pore-water pressures prompts the propagation of failure to large depths, resulting in a slow to extremely slow landsliding [CRUBEN and VARNES, 1996] in slopes of even small inclination [10°-12°; COTECCHIA et al., 2011]. Therefore, the research has been aimed at interpreting the sources of the large piezometric heads that predispose the slopes to instability and the external causes that trigger the slope accelerations. The study started from investigating the extent to which the discontinuities within the soil masses location of landsliding increase the average permeability of the slopes and allow for the existence of high piezometric heads at large depths. This has been carried out taking into account both the fissure network at the meso-scale (i.e., cm to dm scale; VITONE and COTECCHIA, 2011, VITONE et al. 2012, VITONE and COTECCHIA, in prep.) and that at the macro-scale (tens of metres).

Experimental evidence of the recurrent effects of slope-atmosphere interaction in the region is shown in figure 3. This reports in a single plot the variations in piezometric head logged by two Casa-grande piezometers installed in a clay slope location of a deep slow-moving landslide body, the Pianello landslide (Bovino, Bo in Fig. 2), and the displacement rates logged along an adjacent inclinometer, 46.5 m deep. The piezometers are at 36 m and 59.5 m depth and, despite allowing only for a discontinuous monitoring, they give evidence to slow variations in piezometric head, that reach about 2-3 m and are seasonal. The piezometric heads are found to cycle yearly, from the lowest values at the end of summer to the highest in mid spring, as expected for seasonal rainfall infiltration. However, the novel finding that the monitoring here recalled is allowing for, is that such piezometric cycling occurs in the slopes from small to very large depths, despite the main lithotypes in the slopes are clayey. Such cycling is evidently effect of a slow, but important cumulated feeding of the seepage domain down to large depths. As will be shown later, predisposing factors of this piezometric response are both the fractured and coarser soil interbeddings characterizing the flysch formations within the slopes and the fissured nature of the clays, both increasing the average slope permeability. The discontinuous piezometric data suggest that the timing of the piezometric cycling is similar at different depths, but a more accurate assessment of the exact timing of this cycling would require a continuous monitoring, that is not available to date.

The rates in figure 3 refer to the displacements along a slip surface found at 47.5 m depth. Trends of seasonal variation in piezometric head and displacement rate similar to those in figure 3 have been logged in several slopes of the region and are confirmed by the Pisciolo slope data presented in the following. It appears that the deep displacement accelerations accompany the rise in piezometric head from the end of summer to early spring and that, therefore, the piezometric rising down to significant depth is the trigger of medium depth to deep landslide acceleration. Numerical modelling of the seasonal rainfall infiltration and evapo-transpiration in the Pisciolo slope will be shown to predict similar piezometric variations, sufficient to bring about slope instability.

As shown in figure 3, the piezometric heads at Pianello follow a seasonal trend of variation consistent with that applying to the 180 day cumulated rainfalls. This correspondence, later validated through the slope-atmosphere interaction modelling, suggests that for deep landslides in clayey turbidites the threshold climate variable to be accounted for in alert strategies for risk mitigation is the cumulated rainfall, rather than the intensity and duration of rainfalls.

2. The Pisciolo case study

The Pisciolo hill-slope (Fig. 1) is located on the right side of the Ofanto River valley, in the Lucanian Apennines (Fig. 2), and its current geological setting is closely related to the geological history of this chain. As discussed later in some detail, the hill-slope is formed by sedimentary successions, largely clayey, deposited in a pre-orogenic marine basin (Cretaceous-Miocene), thereafter involved in the Apennine orogenesis.

A slow complex landsliding occurs over the whole hill-slope, determining a landslide basin, where up to 14 landslide bodies involve clayey soils (Fig. 4). Some of the landslides interact at the toe of the hill-slope with important infrastructures: an aqueduct pipeline, a national road and a railway (Fig. 1). In the last decade these infrastructures have undergone recurrent damage; in particular, the aqueduct pipeline, that lies at 4 m depth below ground level (see the vents at the ground surface, that are connected to the pipeline underground), has been severely distorted by the cumulated slope movements and has experienced yielding and damage. The high landslide risk prompted the Apulian Aqueduct Authority to fund a comprehensive investigation and
monitoring of the slope. 30 boreholes were drilled (up to 80 m deep), of which 14 continuously cored (Fig. 4). Most of them were equipped with either piezometers (Casagrande or electrical) or inclinometers and were also site of undisturbed sampling for a comprehensive laboratory investigation of the mechanical and hydraulic properties of the soils. Also, GPS monitoring of outcropping sensors connected to the pipeline was carried out (Fig. 4).

Figure 4 reports the geomorphological map of the Pisciolo hill-slope as resulting from current field surveys, stereoscopic analysis of aerial photos taken in 2003 and the interpretation of the results of the investigations at depth, as will be fully discussed later in the paper. The map is introduced here to present the instability processes currently active on the hill-slope and compare them with those active in the past, as shown in the geomorphological map deduced from the stereoscopic analysis of the 1955 aerial photos, shown in figure 5. From the comparison between the two figures it emerges that in 1955 large part of the wide landslide bodies currently active on the slope were either absent, or much smaller. In particular, at the time, the Pisciolo gorge, that crosses the centre of the hill-slope from West to East, was much deeper and represented one of the main segments of the hydrological network on the hill-slope. Then, only thin soil slips with toe about the gorge were active on its sides. North of Pisciolo gorge, instead, a couple of the currently active large bodies were already present, although smaller and with ill-defined toes.

The temporal geomorphological analysis provides evidence of an enlargement and deepening of first failure processes in the hill-slope in the last 60 years, bringing about the current activity of large sliding bodies. The deepening of first failure appears to have developed while the cross section of the Pisciolo gorge was undergoing a major reduction due to the movements of the soil masses on both its sides and to debris filling. It might be inferred that the deepening of first failure has resulted from an increase in infiltration rates prompted in the last 60 years by the loss of draining efficiency of the Pisciolo gorge. Indeed, the current piezometric heads in the slope are very high at depth, and undergo seasonal fluctuations. Figure 6 reports the monitoring data logged at the toe of the Pisciolo gorge (Fig. 4): the piezometric levels for the piezometers at 15 m and 36 m depth down borehole P7, the rates of displacement of the pipeline logged by the GPS sensor S2, along with the displacement rates monitored along a shear band logged between 17 m and 19 m depth down inclinometer I12. As recurrently monitored, these fluctuations seem about synchronous with the 180 day cumulated rainfalls (Melfi weather station).

The data from the Pisciolo hill-slope introduced here show how it is a pilot site for the investigation and modelling of the class of slope-atmosphere interaction processes of interest. In the following, the comprehensive dataset of the slope factors is discussed first, to introduce properly the modelling of the effects of the yearly rainfall infiltration and evapo-transpiration on the piezometric heads in the southern portion of the Pisciolo hill-slope. At this stage, the modelling of the seepage conditions evolving during the year has been not fully coupled, because aimed at identifying a hierarchy among the hydraulic and climatic factors influencing the seepage processes. Based on the results of this modelling, fully coupled modelling of the stress-strain conditions in the slope evolving with climate is currently on-going.
Fig. 3 – Pianello landslide (Bovino, Bo in Fig. 2): displacement rate at 46.5 m depth down inclinometer I2, piezometric levels measured at 36 m and 59.5 m b.g.l. and 180 day cumulated rainfall.

Fig. 3 – Frana Pianello (Bovino, Bo in Fig. 2): velocità degli spostamenti misurati in profondità a 46.5 m lungo la verticale inclinometrica I2, livelli piezometrici misurati a 36 m e a 59.5 m sotto il piano campagna e la cumulata di pioggia a 180 giorni.

Fig. 4 – Pisciolo hill-slope: geomorphological map, reporting also the site investigations. Key: 1) landslide basin; 2) active and 3) inactive deep landslide: a-crown, b-body; 4) shallow landslide; 5) field investigation: S-GPS sensor, P-continuously cored borehole equipped with piezometers, CI: continuously cored borehole equipped with inclinometer casing, I: destructive borehole equipped with inclinometer casing.

Fig. 4 – Carta geomorfologica con ubicazione dei sondaggi prognostici eseguiti lungo il versante Pisciolo. Legenda: 1) bacino di frana; frana profonda attiva 2) ed inattiva 3); a-nicchia di distacco, b-corpo; 4) frana superficiale; 5) indagini geognostiche: S-sensore GPS, P-verticale a carotaggio continuo attrezzata con celle piezometriche, CI: verticale a carotaggio continuo attrezzata con tubazione inclinometrica, I: verticale a carotaggio a distruzione di nucleo attrezzata con tubazione inclinometrica.
Fig. 5 – 1955 geomorphological map. Key: 1) deep ditch; 2) active and 3) inactive deep landslide: a-crown, b-body.

Fig. 5 – Carta geomorfologica riferita alle foto aeree del 1955. Legenda: 1) fosso profondo; frana profonda attiva 2) ed inattiva 3): a-nichchia di distacco, b-corpo.

Fig. 6 – Displacement rates at 17-19 m depth down inclinometer I12 and at ground surface, GPS sensor S2. Piezometric levels at 15m and 36m b.g.l. down borehole P7 and 180 day cumulated rainfall.

Fig. 6 – Velocità degli spostamenti misurati in profondità a 17-19 m lungo la verticale inclinometrica I12 e in superficie in corrispondenza del sensore GPS S2. Livelli piezometrici misurati a 15 m ed a 36 m sotto il piano campagna nella verticale piezometrica P7 cumulata di pioggia a 180 giorni.
3. The geological slope factors

The geological model of Pisciolo hill-slope has been defined as result of geological surveys and analyses of the borehole corings (Fig. 4) and is shown in figure 7. Cretaceous to Miocene turbidites are found to crop out on the hill-slope. Those formed by clays interbedding rock strata are either part of the Red Flysch or of the overlying Paola Doce Formation, at the top of which sandstones, sands and sandy clay layers of the Numidian Flysch occur. After deposition, the strata were folded and faulted during the Apennine orogenesis. Present, the slope is location of a main NW-SE anticline, crossed by a north-dipping sub-vertical normal fault, that runs with a E-W trend (Fig. 7). The Red Flysch occurs at the core of the anticline, while the Numidian Flysch occurs at its limbs, as shown in the geological section in figure 7. The E-W fault is the location of the Pisciolo gorge and divides the hill-slope into two sectors; the northern sector is bordered by the hanging wall of the fault, while the southern one corresponds to the footwall. The Red Flysch outcrops locally at the top of the anticline within the southern side of the Pisciolo gorge. The clays of the Paola Doce Formation are the soils mostly outcropping within the slope (Fig. 7). Some local wedge-top basin deposits (Pliocene sandstones) and Ofanto alluvial sediments occur at the top and at the bottom of the slope respectively.

The soils within the hill-slope are representative of the so-called structurally complex formations [CROCE, 1971], being both non-homogeneous and fissured. The rocks interbedded with the clays are generally fractured and float as disarranged masses in the fine soils (Fig. 8). The soil heterogeneity in the slope is also recognisable from the results of the electrical resistivity surveys performed within the slope (Fig. 7). Several high resistivity (> 25 Ωm) masses, identifiable as rocks, are found floating within a high conductivity (< 6.3 Ωm) matrix, formed by clayey soils. Disarranged rock levels occur at large depth at the toe of the northern sector (e.g., P6 in Fig. 8). More continuous rock intervals are shallower in the toe area of the Pisciolo gorge (borehole P7).
in Fig. 8) and within the toe of the southern slope sector. The frequency of the rock intervals is found to increase when approaching the Numidian Flysch. All these litostratigraphic features influence the seepage flow and piezometric head distribution within the hill-slope.

The fissure network of all the Cretaceous-Miocene clay strata (Fig. 8) occurs along the lamination planes and is mainly vertical, although the spatial distribution of the fissuring is generally irregular. Intense fissuring, as for scaly clays [ESU, 1977; VITONE and COTECCHIA, 2011], is also found in the slope especially in the fault zone (e.g., P3 and P2 in Fig. 8), or along the fold hinge (i.e., P6 in Fig. 8).

According to the lithological and mesostructural features, three main soil complexes were distinguished within the slope, as shown in the schematic lithological map in figure 10 and in the lithological
sections in figure 11. Quartz sandstones, including at places thin clay levels, have been distinguished as Numidian Complex, N. Scaly clays, including calcarenite blocks, as Red Complex, R. A Transition Complex, T, includes all the clayey soils and rocks deposited in the marine basin during the gradual transition from the deposition of the R Complex to the clastic sedimentation of the N Complex. Complex T has been further divided into two sub-complexes: an upper Sandy Transition, ST, and a lower Calcareous Transition, CT (Fig. 10). ST is formed of laminated and fissured clays including mainly sandstone or breccia levels (Fig. 10). Clays, fairly less rich in sand and of higher plasticity belong to the sub-complex, CT, which includes mainly calcareous strata. The thickness of the rocky levels within both the sub-complexes ranges from some centimetres to metres. The frequency and the thickness of the rocky levels seem to increase upwards, within complex ST (Fig. 11), the transition between the two sub-complexes being gradual. Sub-complex CT outcrops extensively in the fault-hanging wall, North of the Pisciolo gorge, and in the northern portion of the bottom of the river valley. In this area, complex R is not deep, as recognized by the increase in calcarenite levels (Fig. 11).

4. The geomechanical slope factors

4.1. Composition and physical properties

Landsliding on the hill-slope is controlled by the strength of the clay strata, whose mesostructure is mostly close to the type A of Esu’s classification of structural
complexities [ESU, 1977]. This was the reason why the
geo-mechanical characterisation of the materials was
focused on the clayey complexes, ST and CT.

The geotechnical characterisation was based on
laboratory testing of undisturbed samples taken from
the surface down to 80 m depth. All the samples are
especially fine soils, with predominant clay fraction (CF = 37-62%; MF = 30-40%). Two groups of clay samples
could be distinguished based upon the index properties.
Figure 12 shows the grading spindles of the two
groups. The grading spindle of Group 1 clays is char-
acterized by a higher sand fraction and a lower clay
fraction than for Group 2. The grading spindle of
Group 1 clays is characterized by a higher sand fraction and a lower clay
fraction than for Group 2. The figure also shows the grading of a typical sample of sandy silt (SF = 53.2%;
GF = 1.8%) from Complex N. The average plastici-
ty index, PI, of the clays belonging to
Group 1 (PI1 = 33%) is lower than that of the clays of
Group 2 (PI2 = 45%). This difference has to be ascribed to their differ-
ent silt fraction, since both the clay groups are of
high activity (Aav = 0.85), and they can be in general
classified as CH. The clay consistency index is gener-
ally high (CIav = 1.25). Clays of both groups occur in
any of the clayey complexes, R, ST and CT, although
Group 1 clays are found to be slightly more recurrent
in sub-complex ST and those of Group 2 in CT.

The meso-fabric of the clay samples has been characterized according to the fissuring characteri-
ization chart (Fig. 15) proposed by Vitone and Cotec-
chia [2011]. Within this chart, each fissured soil cor-
responds to a set of coordinates that represents the
soil ‘Fissuring IDentity’ (F-ID). Categories A and B
characterize the lithology and consistency of the
soil elements between the fissures. The discontinu-
ity nature, orientation and geometry are character-
ized through categories C to I. The categories that
appear to influence most the fissured clay behaviour
are the fissuring orientation (F, from single, F1, to
random, F3) and intensity (I).

The clays of the two groups are found to differ
also for mesofabric and, in particular, for the consist-
cy of the inter-fissure clay elements and the fissur-
ing orientation and intensity. Clays of Group 1 (Fig.
13) are stiff to firm (B2-B3), of single fissure orienta-
tion (F1), that mainly follows the lamination planes
and they have fissuring intensity from medium to high (I4-I5). Clays of Group 2 (Fig. 13), are firm (B3), of either random (F3) or single (F1) fissure orientation and of very high intensity (I6).

4.2. Mechanical behaviour

Vitone and Cotecchia [2011] and Vitone et al. [2013a; b] demonstrated, through the investigation of the strain fields developing with shearing for clays of F-IDs similar to those of the clays in the slope, the applicability of continuum mechanics to test and interpret highly fissured clay behaviour. Therefore, following the authors, the clay samples taken in the slope have been investigated in the laboratory by means of element testing (oedometer tests, direct shear tests and triaxial tests) and according to traditional soil mechanics. Some of the mechanical test results are here reported to acknowledge the mechanical soil properties that predispose the slope to be location of displacement accelerations in con-

---

**Fig. 12** – Grading curves of the soils.  
**Fig. 12** – Curve granulometriche dei terreni.

**Fig. 13** – Characterization chart of fissured clays and F-IDs of Group 1 (*) and Group 2 (°) clays.  
**Fig. 13** – Carta di caratterizzazione delle argille fessurate e identità della fessurazione (F-IDs) delle argille del Gruppo 1 (*) e del Gruppo 2 (°).
SLOPE-ATMOSPHERE INTERACTION IN A TECTONIZED CLAYEY SLOPE: A CASE STUDY

 CONNECTION WITH THE SEASONAL PIEZOMETRIC FLUCTUATIONS (Fig. 6).

Figure 14 shows the results of two restrained swelling oedometer tests carried out on two samples, CI1-CI2 and P1-CI2, representative of Group 1 and Group 2 respectively, from similar depths (about 20 m b.g.l.). The figure also shows the index properties and the mesofabric of the samples. Sample P1-CI2 (Group 2) has higher clay fraction, lower consistency and higher fissuring intensity than sample CI1-CI2 of Group 1. As such, the compression curve of sample P1-CI2 plots above that of CI1-CI2. Both the compression curves have a very mild curvature up to high pressures and a poorly defined gross yield (arrows in Fig. 14), as already recognised for other fissured clays. COTECCHIA et al. [2008] showed that gross yielding of fissured soils is not associated to a fragile degradation of structure, as it is for sensitive clays; therefore it cannot be easily identified from the analysis of the compression curve. Furthermore, VITONE and COTECCHIA [2011] show that the compression curves of fissured clays, like the ones sampled in the hill-slope, do not enter the structure permitted space (Fig. 15), on the right of the compression line of the reconstituted clay (i.e., the ICL of the clay, BURLAND, 1990). These features of behaviour will be shown to apply also to the Pisciolo clays from both Groups in a companion paper. Therefore, these clays are characterized by Stress Sensitivity ratios, $S_\sigma = \sigma_\sigma^{*}/\sigma_e^{*}$, COTECCHIA and CHANDLER, 2000; see Fig. 15), lower than one and they are very weak.

The clays of both groups have similar swelling capacity. Table I reports the average values of compression ($C_c$) and swelling ($C_s$) index measured in the tests on both shallow and deep clay samples of the two Groups. As expected, shallow samples of each Group are more compressible than the deep ones. Table I also reports the results of the restrained swelling oedometer test carried out on the sample CI4-CI1 of silty sand, part of the debris cover. All these geotechnical data are here reported in order to show the extent to which the various lithotypes, previously characterized based upon the geological analyses, differ in composition and mechanics.

Tab. I – Average values of the compression ($C_c$) and swelling ($C_s$) index measured during oedometer tests on Group 1 and Group 2 clay samples.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Sample depth</th>
<th>$C_c$</th>
<th>$C_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1 (shallow)</td>
<td>11-17</td>
<td>0.120</td>
<td>0.042</td>
</tr>
<tr>
<td>Group 1 (deep)</td>
<td>&gt; 80</td>
<td>0.083</td>
<td>0.042</td>
</tr>
<tr>
<td>Group 2 (shallow)</td>
<td>6-22</td>
<td>0.168</td>
<td>0.066</td>
</tr>
<tr>
<td>Group 2 (deep)</td>
<td>31-80</td>
<td>0.124</td>
<td>0.042</td>
</tr>
<tr>
<td>Silty sand</td>
<td>11</td>
<td>0.152</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Fig. 14 – One-dimensional compression curves of samples CI1-CI2 (Group 1) and P1-CI2 (Group 2). For each sample, the figure also shows the principal fissuring features (F-IDs), the clay fraction (CF), the sand fraction (SF), the plasticity index (PI) and a picture of the sample.

Fig. 14 – Curve di compressione monodimensionale dei campioni CI1-CI2 (Gruppo 1) e P1-CI2 (Gruppo 2). Per ognuno dei due campioni, la figura mostra anche le principali caratteristiche della fessurazione (F-ID), la frazione argillosa (CF), la frazione sabbiosa (SF) e l’indice di plasticità (PI), oltre ad una foto del campione.
More than forty consolidated undrained triaxial tests (CIU) were carried out on the clay specimens of the two Groups. The clays exhibited a wet behaviour for overconsolidation ratios \( R (= \frac{p'\gamma}{p'}) \) lower than 2 [Cotecchia et al., in prep.], according to critical state soil mechanics. Fig. 16 shows in the \( q, \text{deviatoric stress} - p', \text{mean effective stress}, \) plane the paths followed by specimens of both groups taken within 25 m depth and consolidated to overconsolidation ratios, \( R \), higher than 2. A dry behaviour is exhibited by these specimens from low to medium confining pressures. Clay specimens of \( \text{Group 1} \) exhibited higher strength than \( \text{Group 2} \) specimens. Also, \( \text{Group 1} \) specimens exhibited a more dilative behaviour and less curved strength envelope than \( \text{Group 2} \) specimens, in accordance with the coarser composition of \( \text{Group 1} \) specimens and, possibly, with their larger overconsolidation ratios. A purely frictional \( (c' = 0\text{kPa}) \) peak strength envelope representing the average strength of the samples from both groups is represented by \( \phi' = 20.7^\circ \) (Fig. 16).

Drained triaxial (CID) tests were carried out on the silty sand sample CI4-CI1. The peak strength envelope measured for this sand reduced from 38° to 28° for \( p' \) values increasing from 50kPa to 150kPa.

Fissuring orientation varies from random (F3) to vertical (F1) for the slope clays and plays a not-negligible role in determining variations in clays strength [Vitone et al., 2013a, b; Cotecchia et al., in prep.] and, as shown later, in the slope permeabilities. In particular, a reduction of peak friction angle up to 28% has been measured in direct shear tests on the Pisciolo clay samples when going from vertical (F1/90°) to horizontal (F1/0°) fissuring orientation. However, the lowest peak strength \( (F1/0^\circ \text{specimens, } \phi' = 20.6^\circ) \) is higher than the residual one, measured in direct shear tests with reversal \( (\phi'_r = 16^\circ \text{ for } \text{Group 1} \text{ clays and } \phi'_r = 13^\circ \text{ for } \text{Group 2} \text{ clays}) \). Therefore, a reliable prediction of the available clay strength in

---

**Fig. 15** – Framework of compression behaviour of I6-I5 fissured clays compared to that of the sensitive unfissured or reconstituted clays [Vitone and Cotecchia, 2011].

**Fig. 15** – Quadro del comportamento in compressione delle argille fessurate I6-I5 a confronto con quello delle argille sensitive non fessurate e delle argille ricostituite [Vitone e Cotecchia, 2011].

---

**Fig. 16** – Stress paths followed by clay specimens of both the groups \( (p' < 300\text{kPa}) \) during consolidated undrained triaxial tests. \( \text{Group 1: empty symbols; Group 2: full symbols.} \)

**Fig. 16** – Percorsi di sforzo \( (p' < 300\text{kPa}) \) seguiti da provini di argilla fessurata di entrambi i gruppi durante prove triassiali consolidate non drenate. Gruppo 1: simboli vuoti; Gruppo 2: simboli pieni.
SLOPE-ATMOSPHERE INTERACTION IN A TECTONIZED CLAYEY SLOPE: A CASE STUDY

47

GENNAIO - MARZO 2014

the slope should account for the orientation of the clay fissuring.

5. The landslide mechanism

The landslide mechanism active on the Pisciolo hill-slope is here presented as resulting from data analyses and limit equilibrium back-analyses, in order to provide knowledge about the context of the slope displacements that appear to be triggered by the slope-atmosphere interaction analysed in detail in the following sections. The geomorphological map in figure 4 is superimposed on the schematic lithological map in figure 10 and geomorphological sections are shown superimposed on the lithological sections in figure 11. The sections give evidence to the important lithological mega to macro-scale heterogeneities characterizing the slope, which are reflected in variations of the permeability coefficient and stiffness modulus across the slope, both strongly affecting the transient seepage from small to large depths. At present, ten large landslide bodies are moving at rates from few millimetres to tens of centimetres per year; faster landslides are shallow and nested in the larger bodies [COTECCHIA et al., 2012].

With reference to the northern slope sector, bodies F and L extend downslope further the railway line, almost reaching the Ofanto River, and involve mainly the clays of the CT sub-complex. The morphology of this slope sector is fairly hummocky and only some ground failures have been recognised within it. On the other hand, most of the landslides located within the southern slope sector, have elongation SE-NW (Fig. 10). In particular, as shown in section b-b’ in figure 11, bodies C9 and C are nested in body A and share the same landslide toe, which emerges within the Pisciolo gorge. They involve the soils belonging to complex R and to both the sub-complexes, ST and CT (Figs. 9 and 11). Their toe does not reach the Ofanto River due to the more frequent rock levels present at shallow to medium depth at the toe of this hill-slope sector (Fig. 11). Several escarpments, ground failures and local small depressions, give evidence to the severe activity of landslides C9 and C. In the following, attention is focused on the failure processes involving bodies C9, C, A.

Figure 17 shows the inclinometer readings for the southern sector of the hill-slope. In detail, figure 17a reports the data for inclinometer I12, within the toe of bodies C9, C and A, which give evidence to an active shear band at 17 to 19 m depth, where the average displacement rate has been 4.5 mm/month and the maximum reached even 14.5 mm/month in late winter. These displacement rates are shown in figure 6 and represent the activity of bodies C9 and C along the slip surfaces shown in figure 11, the first one nested in the second one. The data logged down inclinometer I15 (Fig. 17b) give evidence to displacements only down to 2.5 m depth, here-forth suggesting that the toe of the sliding bodies C9 and C is located either by the road or just beyond it. Inclinometer I5 (Figs. 17c, 4 and 10) is located upslope, within landslide body A. The data in figure 17c show that the soils above 60 m depth moved very slowly in the direction parallel to the longitudinal axis of body A in 2010 and 2011, at about 0.5 cm/year; a reduction of displacement occurs from 60 to 75 m depth, whereas no displacements have been monitored in the deepest 5 m of the inclinometer casing. These data, along with the results of the temporal geomorphological analysis discussed earlier, suggest that an early stage of shear strain localization is slowly developing at large depths upslope in the southern sector of the Pisciolo hill-slope and that the movements of body A are resulting from first failure processes at large depth. The shear strains involving inclinometer I5 are likely to represent the upslope progression of slope failure that, at the toe, is in a more advanced stage.

As discussed previously, the displacement rates recorded down inclinometer I12 and at the ground surface by means of the GPS sensor S2 (Fig. 6), vary seasonally, becoming maximum at the end of winter/early spring and minimum at the end of summer, in accordance with the seasonal variations of the 180 day cumulated rainfalls. A similar trend characterizes the piezometric heads down borehole P7, the same as in several other piezometers installed in the hill-slope, from 13 to 80 m depth (see the data plotted in Fig. 18). The monitored seasonal variation in piezometric head, ranging from 0.5 to 4 m, produces a cyclic variation of the available strengths in the slope. Therefore, the data in figure 6 suggest that the seasonal increase in piezometric head may be a factor triggering displacement acceleration of bodies C9 and C, the same as the seasonal piezometric excursions shown in figure 18 may be triggering displacement acceleration and/or progression of failure in the other portions of the hill-slope, given the strength properties of the soils previously presented. Therefore, it is worth to investigate how this trigger is connected to the hydraulic features of the soil complexes and to the climatic factors applying to the hill-slope, as discussed later in the paper.

Limit equilibrium back-analyses have been performed for landslide bodies C, C9 and A [MORGENSTERN and PRICE, 1965], in order to assess the operational strength currently mobilised along the shear bands. These back-analyses were conducted with reference to the geometry of the landslide bodies shown in figure 11. The limit equilibrium analyses implemented piezometric heads monitored at the end of winter (Fig. 18), in order to evaluate
the strengths mobilized in the period of most active landsliding. The results of the back-analyses are reported in table II. The shear strengths mobilized along the shear bands of both bodies A and C appear to be close to the average peak shear strengths measured in the laboratory. Such similarity confirms that the soils in the shear band of these two landslides are experiencing first failure and that movements take place when the piezometric heads reach the maximum values, although the shear band of body C is currently fully developed, whereas that of body A is still developing. On the contrary, post-peak shear strengths, or even close to residual, are mobilized along the slip surface of body C9, evidently due to a longer activity of this landslide body. At present, both bodies C and C9 (Fig. 6) are experiencing cyclic reactivation [Leroueil, 2001], here considered to be effect of the piezometric excursions shown in figure 6. The increase of about 5-15% in stability factor for these bodies, when the piezometric levels reduce from the winter to the summer values at depths from shallow to large (strength parameter values mobilized in the winter reactivations: $F = 1$ in winter; see Tab. II), confirms that the piezometric excursions may be the reactivation triggering cause.

6. Hydraulic characterization of the slope

Numerical modelling of the hydraulic processes that bring about the piezometric level cycling of the type shown in figures 3 and 6 has been performed with reference to a section of the southern sector of the Pisciolo hill-slope, as representative of the slope conditions where such processes take place. To this aim, the values of all the modelling ingredients have been derived from the studies performed on this hill-slope, which have been...
presented in the previous sections, except for the hydraulic characterization of the slope clays, that is presented in the following. This characterization has been carried out through both laboratory and in-situ testing. The saturated permeabilities were evaluated by means of oedometer tests [Lambe and Whitman, 1969] in the laboratory and through in-situ permeability tests [Tavenas et al., 1990]. Moreover, undisturbed shallow soil samples (Fig. 19) were taken at different times in the year: March, May, July, August 2012 and March 2013, at the sampling site shown as S in figure 10, at depth from 0.5 to 2 m, by means of an on-purpose built ring kit. They were 10 cylindrical samples, of 50 to 56 mm diameter and 20 to 40 mm height, of clay (CF = 61.0%), of high plasticity (PI = 29.47%, Gs = 2.737) and characterized by very high fissure intensity (I6) and random oriented fissures (F3). These have been subject to oedometer testing for indirect permeability measurements and to either drying or wetting tests, in order to derive the water retention curve, WRC, of the soils located above the water table in the hill-slope during part of the year. During these evapo-transpiration rates at the top boundary of the slope.

6.1. Laboratory and in situ measurements of the saturated permeabilities

The saturated permeability values, \( k_{sat} \), were deduced, at the scale of the soil sample, interpreting consolidation data [Terzaghi, 1923] from oedometer tests on fissured clays belonging to either of the Groups, 1 and 2, distinguished in the hill-slope. Figure 20 reports the e-log \( k_{sat} \) plot during the one-dimensional compression of the natural fissured clay samples, from either Group 1 or 2, or of the same sample when reconstituted in the laboratory [Burland, 1990]. The data in the figure are meant to contribute to the definition of the general framework of permeability variation among fissured clays of different fissuring identity, that is an element of knowledge seldom dealt with in the literature [Urciuoli, 1994; Comegna, 2005]. For the natural fissured samples, \( k_{sat} \) results from the combination of both the very low hydraulic conductivity of the high plasticity clay elements between the fissures and the high permeability of the fissures [Federico and Musso, 1990]. Given the important role played by the fissures in conferring higher permeabilities to the investigated materials, all the data were analysed in the light of the clay fissuring intensity, I, and orientation, F, according to the characterization chart in figure 13. In figure 20 the data for the deep samples are reported with continuous lines, those for the samples taken at site S (Fig. 10) at shallow depth are reported with a dashed line and the reconstituted clay data are reported with a dotted line.

Figure 20 shows that \( k_{sat} \) is higher when the soil is in its natural fissured state than when reconstituted, whatever is the fissuring intensity and orientation. In particular, the fissures allow the material to reach permeability values of even two orders of magnitude higher than those of the same material when reconstituted. \( k_{sat} \) of the tested clays range from \( 5 \times 10^{-10} \) to \( 10^{-12} \) m/s when going from the undisturbed state to the lowest void ratios approached at \( \sigma_v=5000\)kPa. These \( k_{sat} \) values are close to those measured in the laboratory for other scaly clays, such as the scaly clays (I6) from Senerchia, Santa Croce di Magliano [Vitone et al., 2005; Vitone and Cotecchia, 2011], Bisaccia [Olivares, 1997; Picarel-
From figure 20 it appears that, for a given fissuring intensity, $k_{sat}$ is higher when fissuring has a single orientation parallel to the hydraulic flux direction (i.e., $F_1-90^\circ$). When the orientation of the fissures is single, but orthogonal to the flux direction (i.e., $F_1-0^\circ$), $k_{sat}$ appears to be either comparable or even lower than that measured for clays of random fissure orientation, $F_3$. Moreover, for a given fissure orientation, less intensely fissured clays ($I_5-I_4$) appear to be more permeable than those of higher fissure intensities ($I_6$), probably because the fissure opening is higher for the less fissured clays than for the more intensely fissured ones.

In-situ permeability measurements were conducted by means of constant head tests in the Casa-grande piezometers using the Mariotte’s bottle. The interpretation of the field test results was carried out following the procedure proposed by Tave- nas et al. [1990] and taking into account the shape factors proposed by Randolph and Booker [1982]. Permeability values about $10^{-9}$ m/s were obtained for the piezometers installed within the clays belonging to either the transition complexes ST and CT. These values are consistent with those measured in the laboratory, since they are only from half to one order of magnitude higher than $k_{sat}$ measured for the samples in the initial undisturbed state [Chandler et al., 1990]. Moreover, the data on the whole suggest that fissuring allows for a much greater infiltration than that generally associated to clay slopes.

### 6.2. Soil water retention behaviour

As previously stated, clay samples from site S (Fig. 10), occurring above the water table, were taken at different times from March 2012 to March 2013 and subjected to measurements of suction and degree of saturation in their undisturbed state, in order to assess the variation in state of the clays at shallow depth on the slope during the year. The suctions measured have been found to roughly range from 30 to 600kPa, as shown in figure 21, with degree of saturation ranging from 70% at the end of August to about 90%. The figure also shows both the drying and the wetting paths followed by the shallow samples in six drying tests and one wetting test respectively, carried out to deduce the WRC of the soils.

During the tests, Whatman No. 42 filter paper, neither pre-treated [Chandler and Gutierrez, 1986], nor pre-dried in the oven [Marinho and Oliveira, 2006], was used to measure the matric suction. For each drying or wetting step of the tests, a couple of filter paper disks was put in intimate contact with

---

**Fig. 20** – Permeability values measured in the laboratory. Key: grey lines: $I_5-I_4$ clay; black lines: $I_6$ clays; asterisks: $F_3$ clays; squares symbols: $F_1/0^\circ-45^\circ$ clays; full circles: $F_1/45^\circ-90^\circ$ clays. Note that the orientation is referred to the plane orthogonal to the flux direction. Dashed line refers to the sample taken at 1.5 m depth in the sampling site S, in Fig. 10. Dotted line refers to the reconstituted clay.
each of the two specimen bases; only one disk was in direct contact with the soil at each base (referred to as in-contact filter paper in the following) and had to act as protection for the other (referred to as non-in-contact filter paper in the following) [BULUT et al., 2001]. An equilibration time of two weeks was waited for each suction measurement [MARINHO and GOMES, 2011] and the calibration curve deduced by LEONG and RAHARDJO [2002] by means of the pressure plate apparatus was used. From the two in-contact filter paper disks, one average suction value was deduced. In the same way, one average suction value was derived from the non-in-contact filter papers. Therefore, in figure 22 full symbols represent the suction data from the in-contact filter papers and the empty symbols refer to the data from the non-in-contact disks. The rhombuses refer to drying, whereas the squares refer to wetting.

The dots represent the matric suction determined by means of the high capacity tensiometers [RIDLEY, 1993; RIDLEY and BURLAND, 1993; RIDLEY et al., 2003]. These measurements were carried out by fixing the tip of the tensiometer in the centre of a perspex disk laid on the basis of the sample for each measurement. A kaolin paste was always spread on the porous tip to guarantee the best contact with the soil. Equilibration time was allowed for each measurement: figure 22 shows the response of two tensiometers, each in contact with one of the two sample bases.

Figure 21a reports the water retention data in terms of volumetric water content, $\theta$, and matric suction, $s$, together with the WRC employed in the numerical simulations, as discussed later. The data give evidence to a good agreement between the measurements performed with the non-in-contact filter papers and the in-contact filter papers for suctions higher than 1000kPa, and this is consistent with the increase in reliability of the filter paper technique for increasing suction. For lower suctions, the values obtained with the filter paper technique are in acceptable agreement with those obtained with the IC tensiometers. Figure 21b reports the water retention data in terms of degree of saturation, $S_r$, against $s$. The figure shows that the samples were characterized by $S_r$ slightly higher than 89% at the start of testing. With wetting, suction has reduced to zero, but $S_r$ has not increased above 90%, most probably due to the presence of the fissures, that confer a multiple porosity to the material and prevent it from approaching $S_r = 100\%$ until fissures are filled up with water.

Finally, the water retention data in terms of void ratio, $e$, against $s$ are reported in figure 21c. All the specimens are seen to suffer from a sudden large reduction in void ratio as soon as suction approaches 1000kPa. As recognized by CAFARO and COTECCHIA [2005] for other natural clays, this high void ratio reduction corresponds to a major entry of air in the clay, called Gross Air Entry Value by the authors [BROOKS and COREY, 1964], that is followed by an increase in desaturation rate. It is worth noting that for the fissured clays under study, this Gross Air Entry is likely to correspond to the entry of air in the elements between the fissures, after that desaturation of the fissures has already taken place.

It can be concluded that the investigated fissured clays are characterized by permeability values higher than those characterizing unfissured clays of the same composition and that this feature prompts
higher rainfall infiltration in the slope. Also, fissures affect the WRC of the clay, that results from the combination of the retention capacity of the fissures and that of the inter-fissure elements. The Gross Air Entry and corresponding major desaturation rates for these clays occur at suctions as high as those sustained by unfissured clays. As such, the fissured clays from Pisciolo are found to sustain very high suctions (about 1000 kPa) at reasonably high saturation degrees (80-90%), as typical for unfissured clays. On the other hand, as for coarse granular cohesionless soils, upon wetting the fissured clay suction becomes null for a degree of saturation well below 100%, due to the difficulty in re-saturation of the fissures and to their very poor retention properties. These hydraulic properties recognized to apply to the fissured clays on the slope are consistent with the evolution in their state during the year, that is found to be subject to a limited drop in degree of saturation with summer drying (not below $S_r = 70\%$), corresponding to quite high suctions that can be retained by the clay at large saturation degree (see Fig. 21).

7. Numerical Modelling of the slope atmosphere interaction

To the aim of predicting the seasonal pore water pressure variations recorded in the Daunia and Lucanian Apennines and shown in figures 6 and 18 for the Pisciolo hill-slope, a class-A uncoupled two-dimensional modelling of the transient seepage in the slope resulting from the slope-atmosphere interaction, has been carried out. All the laboratory and field input data collected in the Pisciolo case study have been implemented in the analyses. The modelling has been specifically addressed to identify the influence on the hydraulics of the slope of the different slope factors: from the lithostratigraphy, to the geo-mechanical and hydraulic properties of fissured clays, to the boundary conditions. As such, in the following it will be shown how the model simulations improve when including, through successive modelling steps, all the slope factors that combine in determining the slope hydraulic response to climate.

The numerical modelling has been carried out by means of the finite element code Seep/w [Geo-Slope International Ltd., 2004], that allows for a full numerical integration of the Richards’ equation:

$$\frac{\partial}{\partial x} \left[ k(h_m, h) \frac{\partial h_m}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k(h_m) \left( \frac{\partial h_m}{\partial y} + 1 \right) \right] + q(t) = \frac{\partial \theta(h_m)}{\partial t}$$

where $k$ is the soil coefficient of permeability, $h_m$ is the pressure head, $q$ is the applied flux at the boundary and $\theta$ is the volumetric water content formulated by the WRC. The code defines as $m_w$ the slope of the WRC, therefore:

$$\frac{\partial \theta(h_m)}{\partial t} = m_w \frac{\partial h_m}{\partial t}$$

In the analyses the only variations in porosity that are accounted for are those due to either suction variations upon drying-wetting, or positive pore water pressure variations upon compression and swelling, once configured by the function $\theta(h_m) = n \cdot S_r$.

7.1. Boundary conditions and mesh

Numerical modelling was performed with reference to the section shown in figure 23 (section b-b’ in Figs. 10 and 11), discretized in a mesh of four-node quadrilateral elements. Elements of 0.2 m height were used close to the ground surface, where time dependent boundary conditions were applied and convergence problems would have arisen if the
mesh had not been properly refined, as suggested by Tsaparas et al. [2002] and Smith [2003].

The upstream hydraulic boundary condition was defined based upon hydrological surveys conducted in different periods of the year. It is worth to say that the hydrological basin of the hill-slope coincides, to a good approximation, with the landslide basin (see Fig. 4). Water pouring from a spring was found in the upper part of the hill-slope (Fig. 10), where the water table could be modelled at the ground surface (Fig. 23). Also, the lateral upstream boundary was set hydrostatic with the water table at the ground surface. Given the presence of the Ofanto River at the bottom of the valley, the water table was set at ground surface at the base of the slope (Fig. 23), where the section intercepts the river. Both the right vertical boundary, crossing the bottom of the Ofanto valley, and the lower boundary of the model were set as impervious.

In the initial steady state analysis (corresponding equipotential lines reported in Fig. 23), along the slope surface (top boundary) it was set a constant head pressure as top value of a hydrostatic condition holding between the ground surface and a water table at 4 m depth. The steady-state analysis was run to define the starting conditions for subsequent transient seepage analyses, during which the slope-atmosphere interaction was simulated. These analyses were carried out implementing a time dependent unit flux at the top boundary, representative of the rainfalls on the Pisciolo hill-slope during a specific year. In particular, the rainfalls recorded at the weather station located in Melfi (PZ), from the 1st of September 2006 to the 31st of August 2007 (Fig. 24a) were input in the analysis as q(t). When q(t) > ksat the code switched the top boundary condition to u=0kPa, to simulate the ponding.

7.2. Hydraulic constitutive properties

The modelled section crosses both the complexes R and T and the Ofanto alluvial deposits. The WRC implemented in the analyses for all the fissured clays in the slope, part of either sub-complexes ST and CT, or complex R, is shown in figure 21a and suites the van Genuchten model [1980]:

\[
\Theta = \frac{\theta_s - \theta_r}{\theta_s - \theta_f} \left[ \frac{1}{1 + (\alpha \psi)^n} \right]^m
\]

under the assumption formulated by Mualem [1976]:

\[
m = 1 - \frac{1}{n}
\]

in which \(\alpha, m, n\) are shape parameters of the law and \(\theta_s, \theta_r\) are the volumetric water contents at \(s = 0\) kPa and at residual respectively. These parameters were selected through a best fitting procedure, using the optimization algorithm RETC [Van Genuchten et al., 1991] and resulted: \(\alpha = 135.734\) kPa, \(n = 1.206, \theta_r = 1.8\%\), \(\theta_s = 45.5\%\).

In order to model the water content increase resulting from the filling up of the fissures, the WRC was forced to fit \(\theta_s = 45.5\%\), assumed to correspond to \(S_r = 100\%\), in order not to neglect the amount of water (10% of \(S_r\)) necessary to fill up the fissures. WRC models capable of reproducing the hydraulic behaviour of multi-porous media will be used in the slope modelling in the future.

The slope of the WRC in saturated conditions (\(\psi > 0\) kPa), \(m_{w_{sat}}\), is strictly related to the compressibility of the soil under oedometric conditions, \(m_v\). For both complexes R and T, \(m_v\) was assumed to coincide with the mean coefficient of one-dimensional swelling measured in the oedometer tests in the range \(\sigma_v = 10 \div 600\) kPa, \(m_v = 5 \times 10^{-5} 1/kPa\).

The hydraulic conductivity function of either complexes R or T was defined using the van Genuchten model [1980]:

\[
k(\psi) = k_{sat} \Theta \left[ 1 - (1 - \Theta)^m \right]^\frac{1}{n}
\]

where \(m\) is the shape parameter of the WRC model proposed by van Genuchten and \(l\) is assumed to be 0.5 [Mualem, 1976]. \(k_{sat}\) was set equal to \(10^{-9}\) m/s for complex T, as measured in-situ and consistent with the laboratory measurements, and equal to \(5 \times 10^{-10}\) m/s.
for complex R. Since the alluvial deposits were completely saturated at any stage of the analyses, their WRC and hydraulic conductivity function in partially saturated conditions did not play any role in the analyses; therefore these deposits were assumed to have the same WRC and conductivity function as the clays on the slope, but with $k_{sat} = 10^{-6}$ m/s and $m_v$ of two orders of magnitude higher.

When simulating the effects on the hydraulic response of the slope of the presence of fractured rock layers within the clays, the fractured rock was assumed to have the same hydraulic properties of the alluvial deposit.

7.3. Total rainfall

In a first set of analyses, it was simulated the transient seepage in the slope consequent to the rainfalls recorded in the year 01/09/2006 - 31/08/2007 (Fig. 24a). The daily rainfalls were implemented as daily in-flow for several subsequent years and evapo-transpiration was neglected. In the first years of rainfall a continuous increase in pore water pressure all way through the slope is found to occur. However, after several years of rainfall, a sort of “rainy regime” is achieved, with the pore water pressures that seem to approach constant values.
These numerical results are plotted in figures 25-26 (grey continuous lines), in comparison with the corresponding piezometer data (black dots) monitored in the slope. In particular, the comparison refers to the piezometers installed at 15 m and 36 m depth down borehole P7 and at 53 m and 80 m depth down borehole P3. The comparison shows that, when neglecting evapo-transpiration, the rise in pore water pressure is too large by comparison with reality, because the flow discharge downslope is not enough to reduce the accumulated water stored in the slope with time.

7.4. Net rainfall

Evapo-transpiration applying to the ground surface of the Pisciolo hill-slope was implemented in a second set of numerical analyses. Monthly evapo-transpiration was evaluated through the FAO Penman-Monteith method [Allen et al., 1998], taking into account the portions of the slope adjacent to the studied section that are location of wheat growth and the area that are largely bare or covered by wild vegetation. In particular, the so called ‘reference evapo-transpiration’, $ET_a$, was evaluated on the basis of the temperature data recorded at the Melfi weather station, with reference to the period 01/09/2006 - 31/08/2007 (Fig. 24b). ‘Crop evapo-transpiration’, $ET_c$, was then derived with reference to the ‘single crop coefficient approach’ for the cultivation named ‘winter wheat’. In this case, the coefficients $K_c$ are referred to the different life periods of the crop as: $K_{ini} = 0.4$, $K_{mid} = 1.15$ and $K_{end} = 0.25$. Finally, the real evapo-transpiration, named as $ET_{c\ adj}$ and plotted in figure 24c, was determined. In particular, for the ‘crop evapo-transpiration’, $K_{ini}$ was reduced accounting for the frequency of the wetting events, the effect of a sparse vegetation covering roughly half slope was taken into account.
and a reduction of 30% of the evapo-transpiration during non-growing periods was considered.

The numerical results of the analyses implementing the net rainfalls at the surface, i.e. the difference between the total rainfalls in figure 24a and the evapo-transpiration in figure 24c, are reported in figures 25-26 (dashed grey lines). The results show that the evapo-transpiration stops the continuously increase in piezometric head and generates extremely low seasonal oscillations of the pore water pressures at shallow depths.

7.5. Reduction in $m_v$

The soil parameter $m_v$ was found to play an important role in the model because it relates the volumetric water content variations occurring below the water table (submerged soil) to the pore water pressure variations. As said before, in the first analyses, which have been discussed so far, $m_v$ was assumed to equal that determined by means of oedometer testing on the clay samples. However, accounting more accurately for the geo-mechanical sequences, it was recognized that due to the larger stiffness of the deeper clays (which increases with confining stress) and the presence in the slope of the recurrent chaotic interbeddings of coarse stiff soil layers and rocks (see Figs. 8, 9 and 11), the mean value of $m_v$ at the slope scale should have been decreased in the subsequent analyses. Moreover, as reported by Bernstorff and Sailfors [1984] and confirmed by L'Hourieul [2001], $c_v$ values deduced from laboratory tests often underestimate the in-situ values, not only because in-situ permeabilities are higher than the laboratory ones, but also because in-situ $m_v$ values need to be evaluated with reference to the small strain shear modulus, in order to obtain reliable numerical simulations of consolidation processes [L'Hourieul et al., 2009]. Here forth, according to a more accurate

Fig. 26 – Numerical results compared with the monitoring data of the vertical P3 (location Fig. 4).

Fig. 26 – Risultati della modellazione numerica confrontati con i dati di monitoraggio piezometrico relativi alla verticale P3 (ubicazione Fig. 4).
simulation of the slope mechanics, \( m_v \) was reduced to \( 10^{-7} \text{1/kPa} \). The corresponding numerical results for net rainfall analyses are shown in figures 25-26 as dotted black lines. The calculated pore pressure fluctuations can be seen to increase with \( m_v \) decrease.

7.6. Organic top soil

The infiltration and evapo-transpiration processes take place mainly across the organic top soil, whose presence has been neglected in the previous set of analyses. At this stage such layer was implemented in the analyses as logged in-situ (Fig. 27) and assuming its WRC and conductivity function to be equal to those used for complexes R and T, but assuming \( k_{sat} = 10^{-8} \text{m/s} \) because of the desiccation fractures and holes generated by roots that had been observed in-situ (Fig. 27). Based upon field observations, the thickness of this layer was assumed equal to 1 m. The presence of the organic top soil allows to obtain pore pressure fluctuations that have the same order of magnitude as those measured in-situ at different depths (see black dashed lines in Figs. 25-26), even if a full agreement with the absolute values of the in-situ measurements seems not to be fulfilled yet.

7.7. Coarse inclusions

A last set of numerical analyses was aimed at implementing, as last slope factor, the presence in the slope of the fractured rock layers, found interbedded within the clay complexes (see Figs. 8, 9 and 11). These layers are characterized by permeabilities of few orders of magnitude higher than for the clay complexes. The numerical modelling was then carried out implementing the more permeable soil portions shown in figure 23. These occur along the verticals P5 and P7 and were simulated as being of permeability \( k_{sat} = 10^{-6} \text{m/s} \). This new input is seen to produce a variation in the piezometric levels that makes the numerical predictions (black continuous lines in Figs. 25-26) much closer to the measured piezometric variations. In fact, an inclusion of material characterized by higher permeability is able to distort the equipotential lines and to reproduce, locally, a distribution of hydraulic head dissimilar from those applying to homogeneous slopes.

Fractured rock layers are found to play an important role both from the mechanical and the hydraulic point of view, because they produce both a reduction in \( m_v \), that amplifies the pore pressure fluctuations and, as a consequence of the higher permeabilities, a redistribution of the pore pressures inside the slope, that allows for a better reproduction of the pore pressures measured in situ.

8. Conclusions

The two-dimensional FEM modelling of seepage in the Pisciolo slope presented in the paper, despite being uncoupled, predicts transient flow conditions in agreement with the field monitoring data and makes evident the current availability of reasonably user-friendly models capable of predicting slope response to climate. Furthermore, the research results contribute to enlighten the scenarios of slope factors to be accounted for when interpreting the sources of diffuse slope instability in chain areas location of extensive clayey outcroppings, such as the south-eastern Apennines. In particular, in addition to the poverty in strength properties of the clays that may occur in tectonically active chains, due to the intense deformations of tectonic origin the soils have undergone, also the piezometric setup is shown to be an internal factor predisposing the slope to instability when the clays are fissured and coarse strata and fractured rocks are dislocated in the clay mass. This is because both the clay fissuring and the interbedding of confined higher permeability layers allow for important seasonal in-flow, that brings about increase in pore water pressure at depth and corresponding decrease in strength that may be crucial for instability.

The model predictions, though, may be improved through further investigation and numerical work. Given the limited data characterizing the climate at Pisciolo, the semi-empirical approach making use of the FAO Penman Monteith method was used to implement evapo-transpiration in the modelling. The results achieved so far provide
clear evidence of the eminent role of evapo-transpiration in the water balance within the slope. This part of the modelling is being improved through physically based simulations of the evaporation and evapo-transpiration flows, that take account of the radiations, temperature, relative humidity and wind at the ground surface [Blight, 1997]. However, in the new analyses the lack of data about relative humidity, radiation and wind at the site imposes several assumptions to be done, on the ground of the knowledge about climate in the geographical context of reference. It is concluded that climate monitoring needs to be fulfilled if appropriate predictions of the slope response are to be achieved.

A multi-modal formulation of the WRC seems to be necessary to reproduce the hydraulic behaviour of fissured clays in a more realistic way than applying the van Genuchten model. This advancement would benefit from a further insight in the wetting response of the clay, also to assess the hydraulic hysteresis of the material, that is suspected to increase the fluctuations in piezometric head at depth.

The analyses have shown the crucial influence on the distribution of the piezometric head in the slope of the heterogeneities in permeability, either inherent to the presence of the top soil at the ground surface or to the interbedding of fractured rocks and coarse strata within the clay matrix at depth. The confined portions of higher permeability and soil stiffness do increase the storability of the slope and the piezometric fluctuations due to seasonal rainfall infiltration. Consequently, the strengths available in the slope undergo seasonal variations that follow the same trend of the 180 day cumulated rainfalls, which, therefore, may be considered the climatic variable of reference in alert strategies to mitigate the risk associated to the acceleration of medium to deep landslides. Research on the threshold values of the 180 day cumulated rainfalls triggering such accelerations should, then, be addressed to the modelling of the infiltration processes, accounting for all the factors found to be relevant in the research. It is expected that the predictions would improve significantly if three-dimensional modelling is developed, allowing for the simulation of all the seepage flow components at depth, especially in presence of complex slope geometry and confined heterogeneities at depth. Therefore, the research is nowadays being continued by developing three-dimensional FEM modelling of the slope processes.

References


SLOPE-ATMOSPHERE INTERACTION IN A TECTONIZED CLAYEY SLOPE: A CASE STUDY
Cotecchia - Pedone - Bottiglieri - Santalio - Vitone


SOMMARIO

L’infiltrazione da pioggia in profondità nei pendii in terreni argillosi viene generalmente considerata un aspetto minore, al limite non influente sulla stabilità di frane profonde. Raramente dunque, le campagne di monitoraggio includono l’installazione di piezometri fino a grandi profondità. Inoltre, la modellazione della filtrazione in profondità nei pendii è spesso non soddisfacente poiché non tiene conto della lito-stratigrafia dell’intero pendio e delle condizioni al contorno di tipo idro-geologico, di rado analizzate con accuratezza.

Il presente articolo fornisce un contributo su quello che si ritiene ad oggi un gap di conoscenza nell’ambito dell’interazione pendio-atmosfera. Nello specifico, la memoria riguarda gli effetti climatici sull’equilibrio a grandi profondità di pendii in terreni argillosi i cui affioramenti sono molto diffusi negli Appennini meridionali in Italia. Tali terreni, spesso parte di roccette tettonizzate, sono generalmente costituiti da sequenze di strati di argille fessurate e rocce fratturate.

L’articolo riporta i risultati di una ricerca su un caso di studio, il versante Pisciolo a Melfi, un sito pilota che ben rappresenta, anche per la sua complessità, gli scenari tipici dei pendii degli Appennini Lucano e Dauno.

In queste aree, le scadenti proprietà meccaniche dei terreni argillosi e le alte pressioni interstiziali sono cause principali della propagazione delle rotture in profondità che portano allo sviluppo di frane, da lente ad estremamente lente, anche in pendii molto poco inclivi.

Principali obiettivi della ricerca sono quelli di investigare le cause degli alti livelli piezometrici che predispongono il pendio all’instabilità ed identificare i fattori esterni che innescano le accelerazioni registrate nel pendio.

Nella prima parte sono discussi il modello geologico di dettaglio del pendio e i risultati della caratterizzazione meccanica ed idraulica delle argille fessurate. La seconda parte riporta i risultati delle analisi numeriche condotte con riferimento ai fenomeni di infiltrazione stagionale ed evapo-traspirazione nel pendio, allo scopo di predire le condizioni di flusso transitorio e verificare la coerenza dei modelli numerici con i dati di monitoraggio di sito.