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Role of the shear zone on the pore pressure regime in an active earthflow

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Abstract

The high deviatoric and volumetric strains induced by slope movements in earthflow bodies can deeply modify the hydraulic and mechanical soil properties. The soil is in fact completely destructured while large cracks continuously form and disappear in the mass; at the same time, a strongly anisotropic shear zone forms at the interface with the basal formation. All that unavoidably affects the current hydrological slope response. Being the long-term landslide activity essentially governed by seasonal pore water fluctuations, the effects of such changes on the mechanical slope response could be not negligible.

Based on data collected during long-lasting investigations and on some simple numerical analyses, the paper discusses the case of an active earthflow in fissured clay shales.

1 INTRODUCTION

Since the Eightees in-depth studies have been carried out by people of the Universities of Naples and Campania on some mechanical aspects of the behavior of earthflows, which widely occur in highly fissured tectonized clays and clay shales present along the Apennine chain (Cotecchia et al., 1986; Picarelli, 1988; Pellegrino et al., 2004; Picarelli et al., 2005; Comegna et al., 2007). Such soils, which have been subjected to intense tectonic events, include both a lapideous and a fine-grained component (Esu, 1977).

In many cases earthflows originate from an even limited slope failure (possibly a slide) in deteriorated stiff clays or clay shales, which overload the deposits located downslope (Hutchinson and Bhandari, 1971). The effect of undrained loading is the development of a moderate to rapid earthflow; while propagating, this replicates on the soils located downslope the process of undrained loading. With time the landslide tends to slow down as a result of excess pore pressure dissipation, the so-called sliding-consolidation process (Hutchinson, 1986). In turn the landslide style changes from flow to slide (Picarelli, 2001). In the last stage, which can cover tens of years or more (Giusti et al., 1996), the landslide takes the features of a slow active slide driven by seasonal pore pressure fluctuations.

An interesting feature of earthflows is their macrofabric (Picarelli, 1993). In fact, this consists of two well distinct parts: i) an upper “earthflow body”, which is highly destructured and remolded by the strong deformations induced by movements and includes large and deep cracks which continuously open and close following earthflow deformations; ii) a thick (up to 1 m or more) shear zone generated by the high deviatoric strains induced by the flow/slide movement style, at the interface with the basal stable formation (Bromhead, 2004). This shear zone has completely lost its original highly fissured fabric and appears as a rather “soft” homogenous soil with an anisotropic microfabric possibly characterized by shear fissures in the slope direction (Comegna and Picarelli, 2008); it seems to thicken with movement, possibly according to mechanisms as those described by Agung et al. (2004), in turn discussed by Picarelli et al. (2006).

The different properties of earthflow body, shear zone and parent formation could significantly affect the hydrological response of the moving mass. This paper provides the main results provided by investigations on the Masseria Marino earthflow in the Basento valley (Southern Italy).

2 THE MASSERIA MARINO EARTHFLOW

2.1 Basic aspects of the landslide behaviour

The Masseria Marino earthflow is active at least since the Seventies of the last century (Giusti et al., 1996). It consists of tectonized clay shales from the Varicoloured Clays formation and covers a 400 m long slope located upslope the alluvial plain of the Basento valley. As typical of earthflows, it presents three different zones: a source area, a main track and a fan shaped accumulation zone (Fig. 1a). The source zone corresponds to an old slide area subject to periodic retrogression, which is usually induced by long-lasting precipitations. Due to retrogression of the main scarp, the alimentation zone discharges clayey debris into a 150 m long and about 30 m wide track. The average angle of the track is about 10° and its depth 4-6 m (Fig. 1b). The track conveys the debris into the accumulation zone located in the alluvial plain of the Basento river.

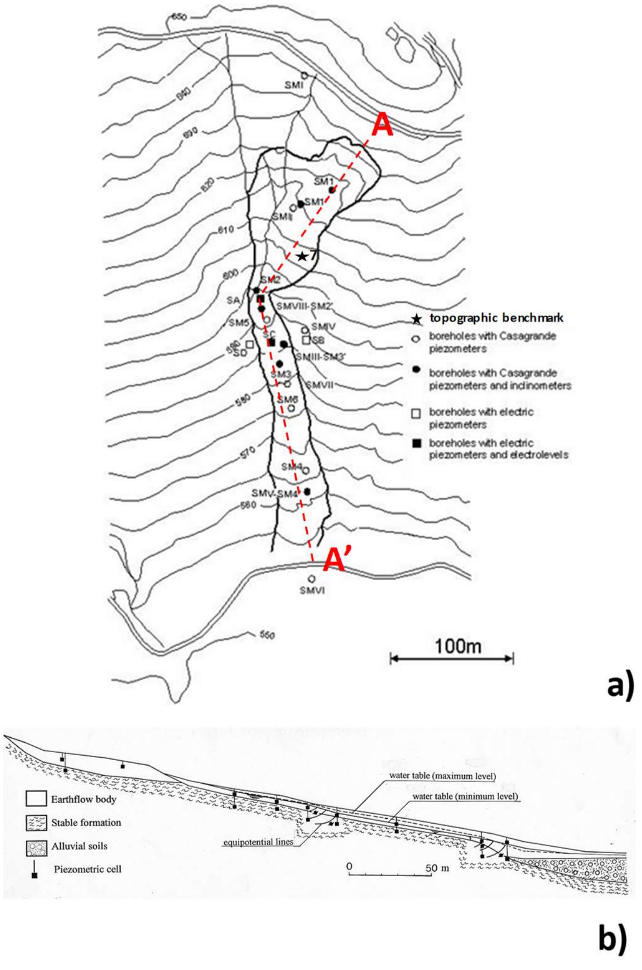

Figure 1. Masseria Marino earthflow: a) plan; b) main section A-A’ (from Giusti et al. 1996).

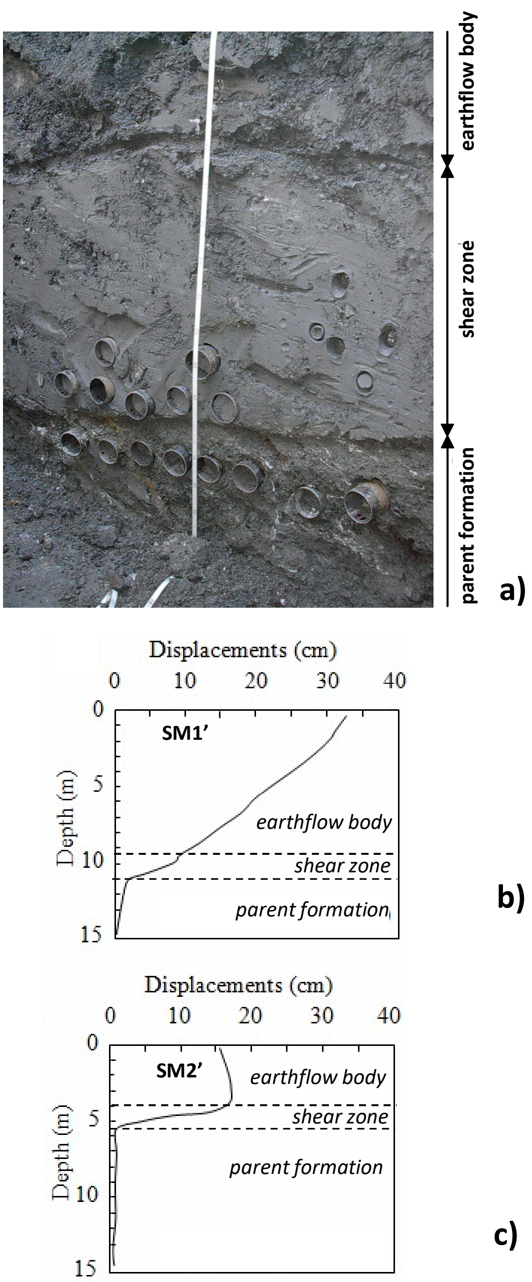

Figure 2. Masseria Marino earthflow: stratigraphic sequence recognized in a pit (a); displacement profiles measured between December 3rd, 1992 and January 21st, 1993 (Giusti et al., 1996) in the source area (b) and in the main track (c).

In the very first stage following slope failure and consequent surging, the mass displays a flow style, i.e. the internal shear deformation prevails over the displacement concentrated along the sliding surface (Fig. 2b), and the displacement rate ranges from moderate to rapid (Cruden and Varnes, 1996). After such stage, the displacement rate tends to gradually slowdown, ranging from slow to extremely slow, and the movement takes a translational slide style, i.e. the displacement is essentially the result of slipping along the sliding surface (Fig. 2c) and of shear strains in the surrounding shear zone, while the uppermost earthflow body displays minor strains. This "slide-style" stage could last even tens of years, unless extreme weather conditions trigger a new surging phase ("flow-style" stage through further retrogression of the source area).

In the "slide-style" stage the behaviour of the landslide is governed by both the high shear stress level and the viscous nature of the soil. Taking into account that the shear stress τ does not significantly change during movement, the stress level is essentially affected by pore pressure fluctuations, which in turn govern the shear strength along the slip surface (residual strength, τ_{res}). The kinematics of the landslide is then a function of pore pressure changes. Figure 3 reports either the piezometric heads measured from 1991 to 1993 by some Casagrande piezometers installed within the landslide body (Fig. 3a) either the displacements monitored by nearby inclinometers (Fig. 3b). The kinematics of the landslide is quite consistent with the pore pressure regime, showing landslide acceleration during phases of the water level rising.

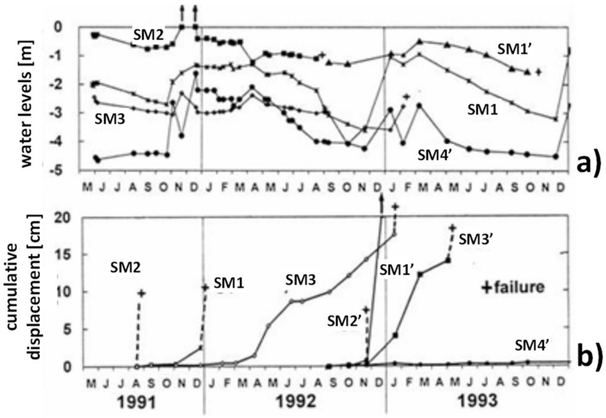

Figure 3. Water levels measured by Casagrande piezometers within the landslide body (a) and horizontal displacements measured by inclinometers (b) in the Masseria Marino earthflow from 1991 to 1993 (from Giusti et al. 1996).

Depending on the pore pressure field, the value of τ_{res} is strictly related to the mechanical and hydraulic properties of the soils in the shear zone. In the following, it will be shown that the properties of this zone can strongly govern the response of the earthflow to precipitations.

2.2 Soil properties

A rich data-base about the properties of the materials involved in the Masseria Marino landslide has been collected thanks to accurate field and laboratory investigations (Urciuoli, 1994;

Guerriero, 1995; Comegna, 2005). A summary of such data is reported in Table 1.

Table 1. Main properties of the soils involved in Masseria Marino earthflow: overall water content, *w*; void ratio, *e*; hydraulic conductivity normal to the slope direction, K_n; hydraulic conductivity parallel to the slope direction, K_t; volume compressibility, m_v.

Soil	*w*	*e*	K_n [m/s]	K_t [m/s]	m_v [kPa^{-1}]
earthflow body	0.18	0.59	2.2E-09	2.2E-09	4E-05
shear zone	0.22	0.67	8.6E-11	4.7E-10	8E-05
parent formation	0.15	0.41	1.5E-09	1.5E-09	2E-05

As discussed, the parent formation is constituted by tectonized clay shales. The schematic representation in Figure 4 shows that the soil consists of small fragments of hard or indurated clay (shear lenses) separated by polished fissures (minor shears). It includes also frequent macro-discontinuities (major shear surfaces). Experience suggests that this material displays a high softening potential. In fact, upon unloading it tends to quickly swell, loosing progressively its peculiar fabric (Picarelli, 1993).

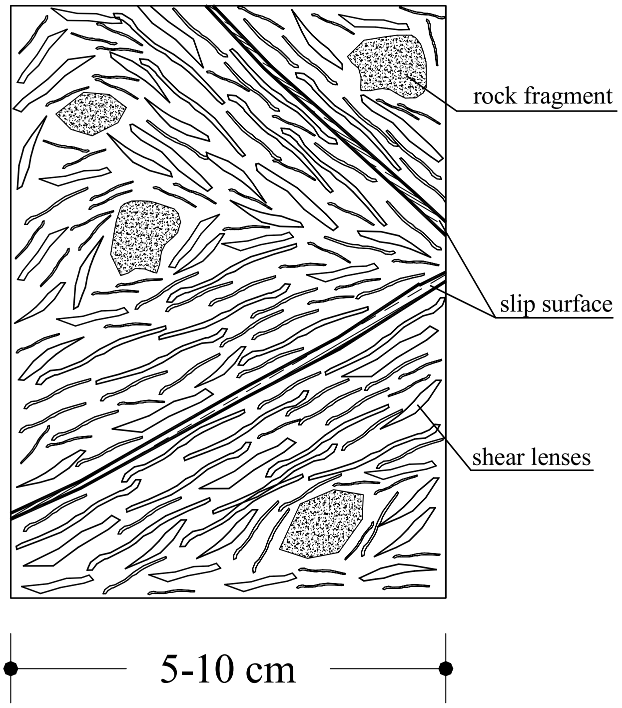

Figure 4. Schematic representation of the fabric of the parent formation (from Comegna et al., 2004).

The fabric of the landslide body is quite different (Fig. 5). In fact, it is constituted by intact hard elements of the parent formation (lithorelicts) and by small lapideous fragments (sandstone, limestone or marl) surrounded by a softer clay matrix. Such a fabric is the result of destructuration and softening induced, first, by natural deterioration phenomena, then, by remolding due to earthflow movement (Picarelli, 1993). Softening seems to be favoured by infiltration of fresh rainwater (Di Maio, 1996).

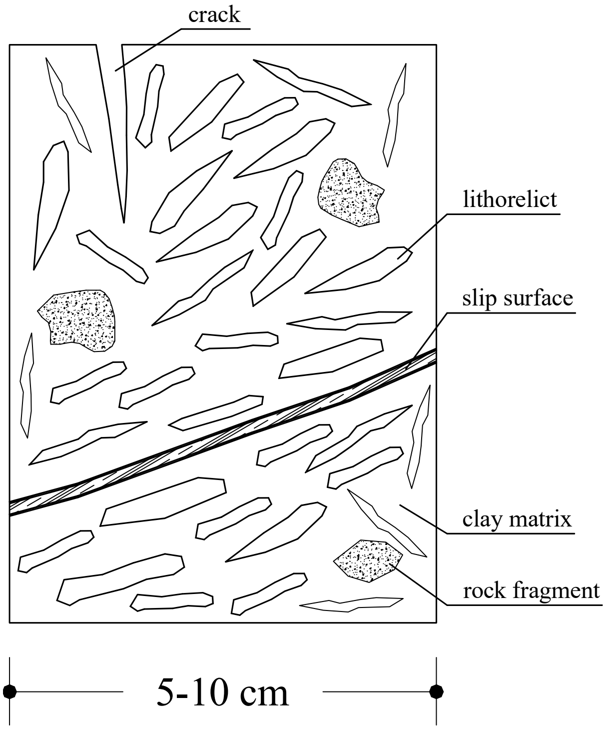

Figure 5. Schematic representation of the fabric of the earthflow body (from Comegna et al., 2004).

The shear zone is completely remolded (Fig. 6). The soil is fully softened and includes a few isolate lithorelicts and rock fragments. If compared to the landslide body, fissuring is less evident. While a principal shear (the slip surface) may be always identified, minor shears are often not distinguishable with the naked eye. At the micro-scale, the clay particles are essentially aligned in the direction of shear (Comegna and Picarelli, 2008). However, since the shear zone should include sets of minor shears inclined to the direction of movement (Riedel, 1929; Skempton and Petley, 1967), clay particles could be locally parallel to them.

The Plasticity Index of the clay shales is about 27%. Regarding the “overall” water content, i.e. the one which may be measured on large samples consisting of both clayey matrix and stiff lithorelicts (Hutchinson, 1988), the mean value characterizing the landslide body (18%) is higher than the one of the underlying stable parent formation (15%), but lower than that of the shear zone (22%). This simple information solely can clearly highlight the effects of slope movements on the soil state.

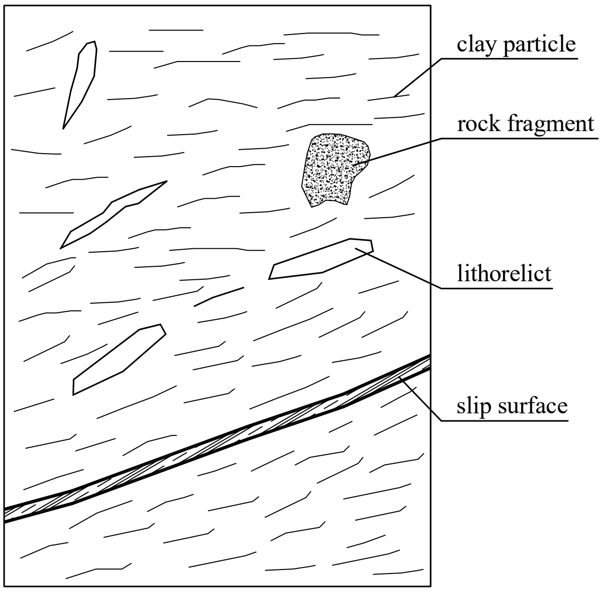

Figure 6. Schematic representation of the fabric of the shear zone (from Comegna et al., 2004).

The effects of soil remolding in the shear zone may be recognized from a comparison of the yield surface of specimens taken from this zone and from the earthflow body (Guerriero, 1995; Comegna, 2005). Such a surface has been obtained thanks to the interpretation of a number of triaxial tests on undisturbed samples located at very similar depths (Fig. 7). The smaller size of the yield surface of the shear zone reveals the effects of the recent stress history, which led to a decrease in the overconsolidation ratio and consequent increase in soil compressibility. In particular, the results of some drained triaxial tests (Comegna, 2005) allowed to estimate a volume compressibility, m_v, of landslide body and shear zone of respectively 4E-05 kPa^{-1} and 8E-05 kPa^{-1} (Table 1). The volume compressibility of the parent formation is instead 2E-05 kPa^{-1}.

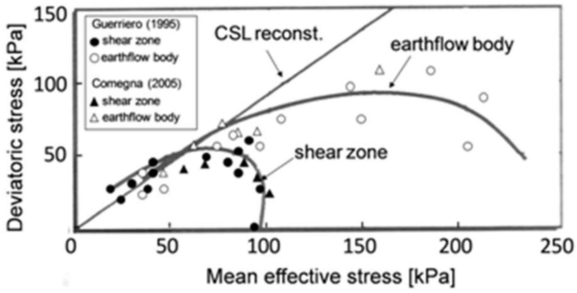

Figure 7. Yield surface of the Masseria Marino earthflow body and shear zone.

The role of fissuring and the soil microfabric have been evidenced by a number of permeability and direct shear tests on undisturbed specimens. Figure 8 shows the results of some constant head tests performed, in situ, by Casagrande piezometers (Urciuoli, 1994) and, in the laboratory, through triaxial cells (Comegna and Picarelli, 2008). The hydraulic conductivity measured by field tests is one order of magnitude higher than that measured by laboratory tests: such result is probably due to the influence of a network of open cracks and fissures. The laboratory tests have been carried out on both undisturbed and reconstituted specimens subject to different confining stresses. The slopes $C_K = \Delta e/\Delta \log K$ of the curves reported in Figure 8, where Δe is the variation of the void ratio and $\Delta \log K$ the variation of the logarithm of the hydraulic conductivity, reveal the different influence of discontinuities on soil permeability. In particular, reconstituted specimens display the highest value of C_K (0.29). In contrast, the lowest values characterise the parent formation (C_K = 0.07) and the landslide body (C_K = 0.04). Finally, intermediate values have been measured on specimens from the shear zone that reveals an anisotropic hydraulic soil response; in fact, the value of C_K in the slope direction (0.11) is lower than that measured in the direction normal to it (0.16). The set of results suggests that in reconstituted soil only considerable changes of the void ratio could lead to valuable changes of the hydraulic conductivity. On the contrary, in the parent formation and in the earthflow body, whose permeability is strongly influenced by discontinuities, even a small increase in the overall void ratio could cause a strong change in soil conductivity, which is mostly due to a change in the opening of fissures (Comegna and Picarelli, 2008). The intermediate response shown by the shear zone suggests that its permeability is also affected by some micro-fissuring, possibly by minor shears.

Summing up, accounting for the different in-situ void ratio (Table 1), the parent formation and the earthflow body are more pervious than the shear zone, being featured by comparable average values, respectively equal to 1.5E-09 m/s and 2.2E-09 m/s. In contrast, the shear zone is the less permeable, displaying a mean value of 4.7E-10 m/s in the slope direction and of 8.6E-11 m/s in the direction normal to it. A preferential alignment of discontinuities and clay particles in the slope direction, i.e. the direction of movement, might be the reason of the hydraulic anisotropy of the shear zone.

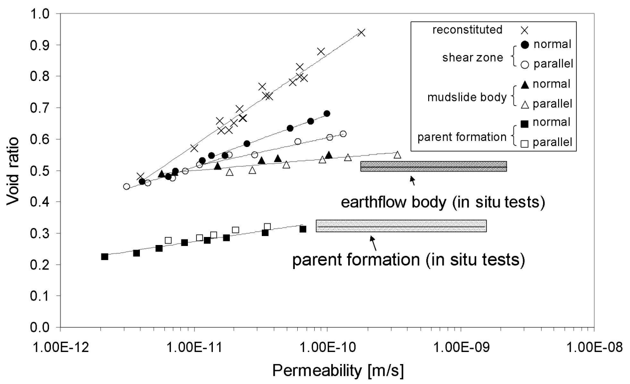

Figure 8. Results of hydraulic conductivity tests carried out in situ (Urciuoli, 1994) and in laboratory (from Comegna and Picarelli, 2008).

The results of some direct shear tests confirm the anisotropy of the shear zone (Comegna and Picarelli, 2008). Figure 9, in particular, shows an evident, even though pretty modest, difference in the shear strength envelopes in the shear zone direction and in the direction normal to it.

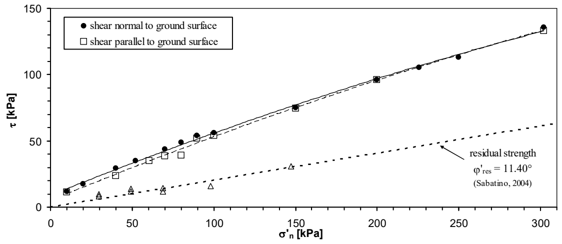

Figure 9. Results of direct shear tests on soil from the shear zone (from Comegna and Picarelli, 2008).

Finally, some direct shear tests performed on natural specimens allowed to measure the residual friction angle, φ'_{res}, which is 11.4° (Sabatino, 2004). This value, obtained by a small number of tests (Fig. 9), is comparable to the value that can be derived from the well known empirical relationship with the Plasticity Index, PI, $\varphi'_{res} = 46.6/PI^{0.446}$ (Kanji, 1974), which provides the value of 10.7°. It's worth noting that a friction angle of 11° is just slightly larger than the slope inclination. This point will be resumed in the next section, which reports and discusses the results of some simple numerical analyses of the hydrological slope response to precipitations.

3 ANALYSIS OF THE HYDROLOGICAL RESPONSE OF THE MASSERIA MARINO EARTHFLOW

As discussed in section 2.1, the displacement rate of the Masseria Marino landslide in the present long-lasting "slide-style" is strongly related to the seasonal pore pressure fluctation along the slip surface. The piezometric regime in the mass, in turn, depends on the hydraulic and mechanical properties of the soils. This problem is usually disregarded also due to the scarcity of data about the properties of the shear zone. Therefore, thanks to the lucky chance to have good data about that, simple 2D F.E. numerical simulations have been carried out in order to broadly assess the response to rainwater infiltration of a slope having the geometric and hydro-mechanical features of the Masseria Marino landslide (Fig. 10). The calculations have been carried out by the SEEP/W code (GEO-SLOPE International Ltd). For the sake of simplicity, a vertical axis of symmetry has been placed through the hilltop, while the total head along the opposite vertical boundary has been kept constant with depth because of the presence of the river. Finally, an impervious horizontal surface has been imagined at a depth of 50 m from the landslide toe. Regarding the initial condition, a negative pore pressure has been imposed at the ground surface in order to reproduce the lowest position of the ground water table as by monitoring at the end of the dry season (i.e. about 4.7 m from the ground surface in the main track). The earthflow body, the shear zone and the parent formation have been considered fully saturated with the compressibility and hydraulic conductivities indicated in Table 1. The effects of precipitations have been simulated by imposing at the ground surface a pore water pressure equal to zero for a period of six months, which corresponds to the usual duration of the wet season in the Basento valley. This boundary condition is equivalent to a constant film of water, which allows a continuous recharge of the groundwater. Such a simplified hypothesis is quite reliable taking into account the low permeability of the soil and the irregolarity of ground surface profile which favours some local water ponding.

Figure 11 shows the evolution of the piezometer level at two different points located at similar depths in the main track (Fig. 10b), respectively in the earthflow body (point P, depth 4.7 m) and in the shear zone (point Q, depth 5.5 m). As a consequence of the hydraulic boundary condition at the ground surface, the calculated water levels display a smooth and continuous rising until the end of the wet season, but with different rates (Fig. 11a). In fact, the pore pressure increase in the earthflow body (point P) is faster than in the shear zone (point Q), and this because of the contrast in permeability at the interface between the earthflow body and the shear zone. In particular, during the first month the water level rising is about 9 cm/day in the earthflow body, in line with the typical monitored response (Fig. 2a), but less than 2 cm/day in the shear zone. Moreover, at the end of the wet season, the depth of the water level in the landslide body and in the shear zone is respectively 0.8 m and 2.5 m.

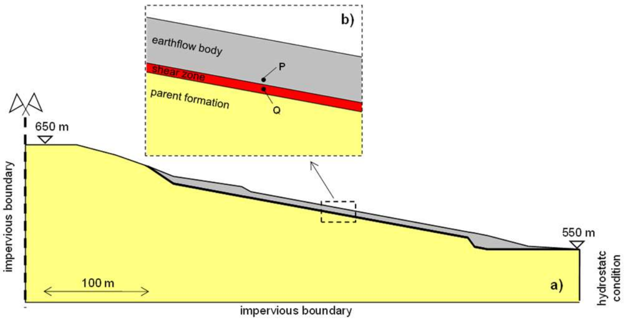

Figure 10. Slope profile and hydraulic boundary conditions adopted in the seepage analyses (a); cross section of the landslide body in the main track (b).

Figure 11b shows the evolution of the local flow direction, which is represented by the angle α that the velocity vector forms with the horizontal. At the beginning of the wet season, the velocity flux in both zones is strongly influenced by the downward rainwater infiltration, displaying rather a significant inclination. In the long term, in the earthflow body, it gradually tends toward the initial steady-state downslope direction, while in the shear zone it is still directed in the vertical direction and this because of continuing swelling of this compressible zone of the landslide body due pore water pressure increase. This of course justifies the low local piezometer levels.

It is noteworthy the fact that the slope stability conditions are strictly influenced by such a special hydrological response. To this aim, some stability analyses have been carried out to assess the influence of the hydraulic regime on the stress level in the main track, by assuming the simplified infinite slope model, which is justified by the nearly constant slope angle and low depth/length ratio of the track (Fig. 10).

Figure 11c reports the values of the mobilized friction angle, at each time step of the seepage analysis, assuming a slope angle of 10° and a depth of the slip surface of 5.5 m. As it can be seen, it ranges between about 10.6° and 13.4°, values that are significantly lower than those that might be calculated by assuming the piezometric levels measured in the earthflow body above the shear zone. It is worth noting that the calculated values are closer to the residual friction angle (11.4°) measured through direct shear tests.

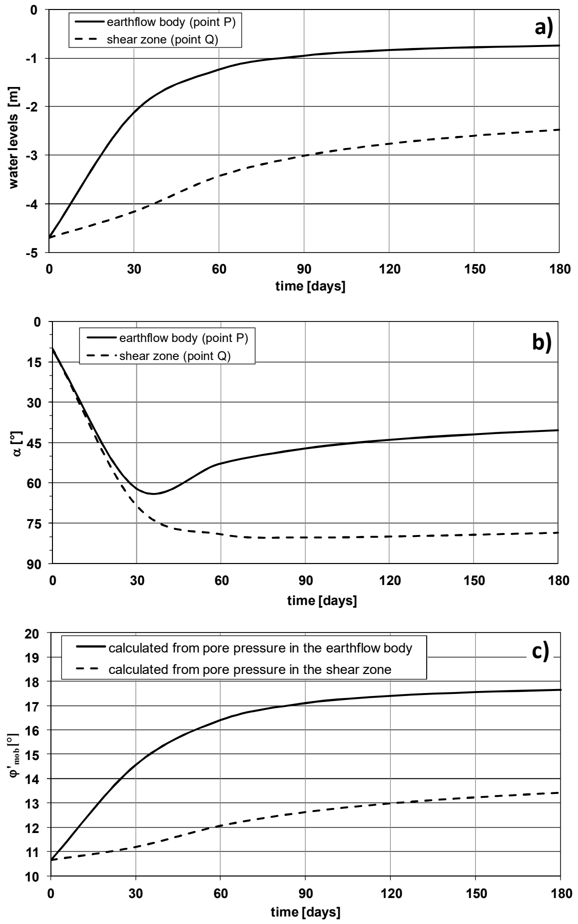

Figure 11. Results of the seepage analyses: evolution of the water level (a) and of the flow direction, α (b), in the main track, within the earthflow body (point P) and the shear zone (point Q); (c) mobilized friction angle.

4 CONCLUSIONS

Investigations carried out on an active earthflow in fissured clay shales show that the intense soil deformations induced by slope movement can significantly affect the properties of involved soils. In particular, in the case at hand the landslide body, which is affected by cracks and fissures, is more permeable than the shear zone and this at least in the direction normal to the slope direction. The shear zone, which is subjected to intense deviatoric strains, is in turn more compressible than the landslide body.

Some numerical simulations of the effects of rainwater infiltration stress that properties can significantly affect the piezometric regime in the landslide body. In particular, the piezometric levels in the shear zone are smaller than those which are attained in the landslide body thus justifying quite a low value of the mobilized friction angle; in particular, this is lower than the value which would be provided by conventional analyses not accounting for the recognized geotechnical details.

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