Features of the shear zone found at the base of a mudslide in clay shales

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ABSTRACT
Mudslides are widespread in Italy and generally involve highly fissured sheared tectonized clay shales. Investigations show that the landslide body moves over quite a thick shear zone containing one or more slip surfaces. This zone includes isolate lithorelicts of the parent formation floating within a completely softened and remoulded clay matrix. The shear zone appears to be slightly overconsolidated and anisotropic, as it is indirectly demonstrated by the results of both permeability and direct shear tests; however also permeability and shear strength seem to be influenced by fissures.

RÉSUMÉ
Les coulées d'argile sont très rapandués en Italie et se dévéloppent surtout dans des dêpots d'argilites tectonizées très fissurées and cisaillées. Les investigations montrent que le sol se déplace sur une zone de cisaillement assez épaisse constituée par une matrice argilleuse complètement rammollie et remaniée dans laquelle sont présentes une ou plusieurs surfaces de glissement. Cette zone semble faiblement surconsolidée et anisotrope, comme indirectement montrent les résultats d'essais de permeabilité et de cisaillement direct; la perméabilité et la résistance au cisaillement semblent influencées aussi par la presence de fissures.

1. FOREWORD

Slope failure in stiff clays and clay shales is generally induced by shear and is characterized by localization of plastic deformations within quite a thin zone, the shear zone. According to the Riedel's experiences (1929), Skempton (1967) stressed that the formation of a shear zone in clay implies the development of minor shears until a continuous shear discontinuity, the principal shear, forms, along which large displacement can develop. In landslides, the principal shear is called shear surface, or sliding or slip surface. The presence of an active slip surface is clearly revealed by inclinometer measurements, that show a discontinuity in the profile of horizontal displacements.

In principle, the shear zone should govern either the groundwater flow, because of its permeability that could be different from that of the landslide body, or the displacement field, because of the high shear strains and displacements that occur respectively within it and along the slip surface (Pellegrino et al. 2004). Despite the role they can play on the landslide behavior, data about hydraulic and mechanical properties of shear zones are extremely scarce, mostly in the case of mudslides.

The present paper contributes to this point, providing some data obtained in investigations carried out by researchers of the University of Napoli, on the Masseria Marino mudslide, Southern Italy (Fig. 1).

2. FEATURES OF THE MUDSLIDE BODY AND OF THE SHEAR ZONE

Mudslides are typical landslides in stiff clays and clay shales. In the Italian Apennines they generally involve highly fissured sheared tectonized clay shales. Usually, first movements following the slope failure are of slide type, but quickly the material softens, progressively taking a flow-like style; after a stage of moderate to fast movement, the mudslide slows down turning again into a slide (Picarelli 2001), unless a new sudden reactivation is triggered.

Italian literature reports a number of cases of mudslides in highly fissured sheared clay shales. Their size is extremely variable: in some cases, they can move several millions of cubic meters (Picarelli and Napoli 2003). Mudslides damage

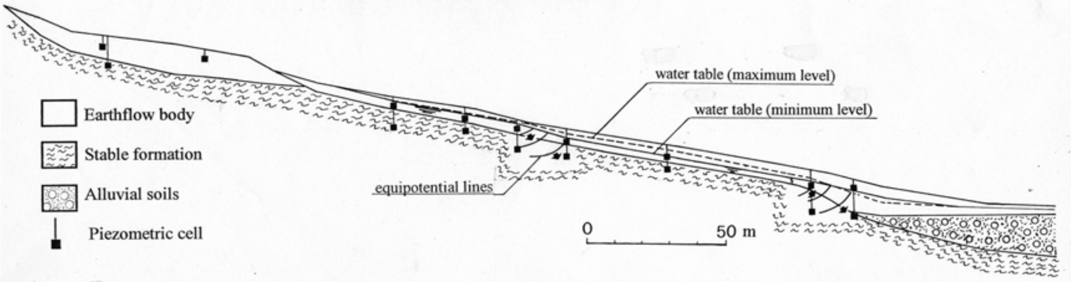
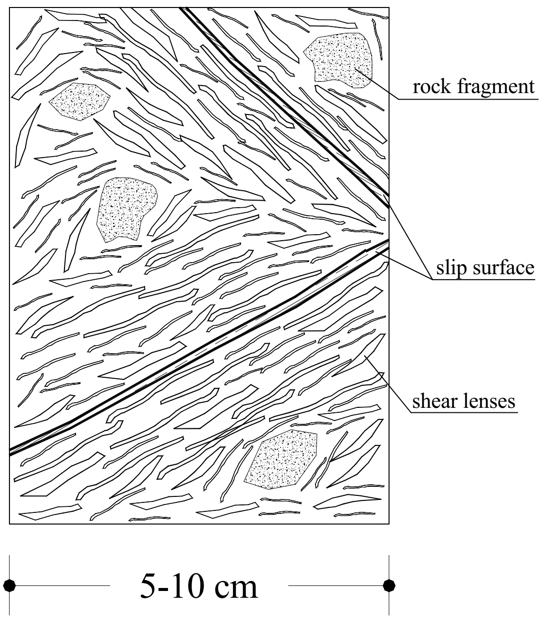


Figure 1. The Masseria Marino mudslide, Basento Valley (from Giusti et al. 1996)

roads and railways, but there are also towns abandoned or seriously damaged by movements (Angeli and Silvano 2003). Tectonized clay shales are constituted by small fragments of hard or indurated clay, separated by polished fissures. In addition, they generally have a high softening potential. In fact, as a consequence of stress decrease, the material can quickly swell, loosing progressively its fabric (Picarelli et al. 1998). Figure 2 shows a schematic representation of a highly fissured sheared tectonized clay shale. It is characterized by macro-discontinuities, as major shear surfaces, and meso-discontinuities, as minor shears (polished fissures). The fissures bound hard millimetric or centimetric shear lenses constituted by hard aggregates of clay particles, that can be slightly bonded (Picarelli et al. 1998). Major shear surfaces and fissures can be opened.

Skempton and Hutchinson (1969) and Brunsden (1984) describe the fabric of clay shales involved in flow-like movements: it is constituted by intact hard lithorelicts (lumps) surrounded by a softer clay matrix. In some formations, as Italian tectonized clay shales, the soil mass may include also lapideous fragments of sandstone, limestone or marl. Vallejo (1989) classifies the soil fabric as a function of the amount of lithorelicts; in particular, he describes a grain supported fabric, a grain-matrix supported fabric and a matrix supported fabric. Similar considerations are reported by Picarelli (1993). Picarelli et al. (1998) stress that the fabric of soils involved in mudslides is a consequence of destructuration and softening due to stress release occurring in some parts of the slope before and after failure, and of remoulding produced by movements, that cause the formation of shear surfaces and tension cracks.



a)

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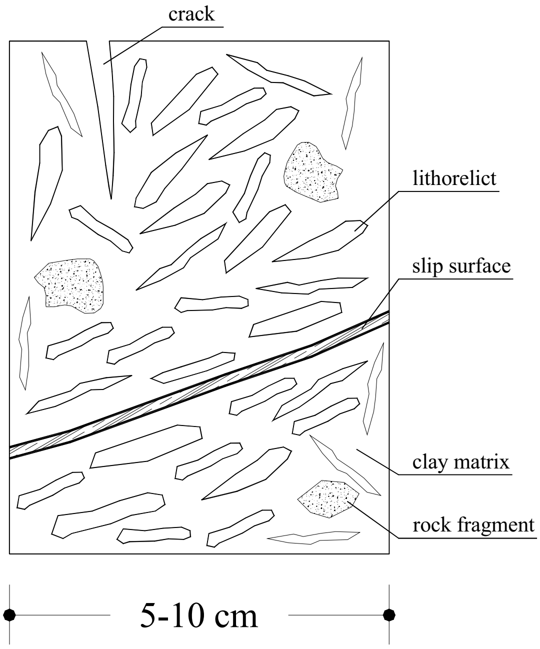
Figure 2. The fabric of highly fissured sheared tectonized clay shales: a) schematic representation; b) a specimen taken from the Masseria Marino clay shale



a)

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Figure 3. The fabric of a mudslide body in highly fissured sheared tectonized clay shales: a) schematic representation; b) a specimen taken from the Masseria Marino mudslide

They suggest that in clay shales of marine origin, softening is enhanced by infiltration of fresh water and consequent changes of the characteristics of the pore liquid. A schematic representation of the material constituting a mudslide body is reported in Figure 3: a softened clay matrix includes lithorelicts and small lapideous fragments; the soil mass is crossed by different discontinuities as shears and cracks.

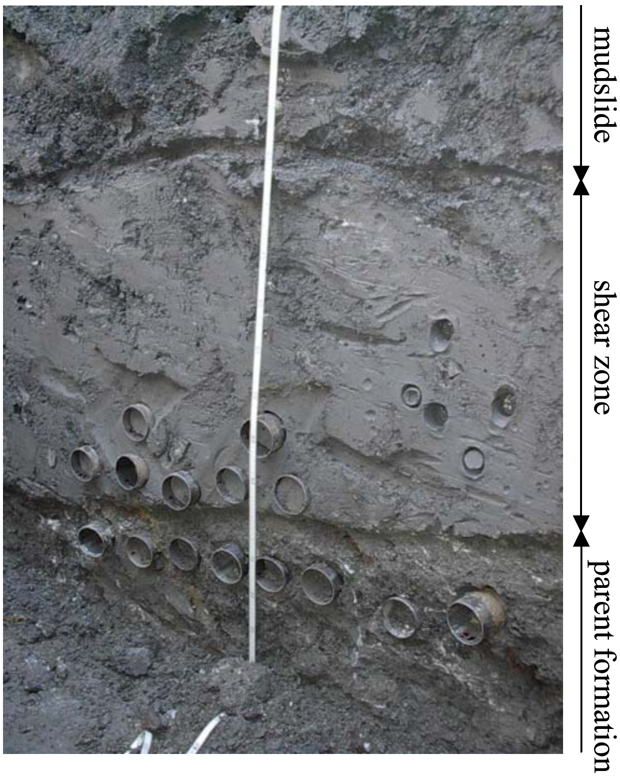

Figure 4. The shear zone found at the base of the Masseria Marino mudslide

At the base of the mudslide body is always present a shear zone (Picarelli 1993) that is quite different from the shear zone described by Skempton and Petley (1967), present at the base of slides. This represents the part of the subsoil subjected to shear failure over which moves the landslide body. In contrast, as a consequence of the large travel distance covered, along the track and in the accumulation zone the mudslide body spreads over the ground surface that is not involved in movements. According to Corominas and Moreno (1988) and Bromhead and Clark (2004), movements produce erosion of the top of the outcrop ran by the mudslide body, that is subject to a sort of subsidence. In fact, in many cases, pits dug until the base of mudslide bodies show that the top soil has been completely removed (Pellegrino et al. 2004). Therefore, the shear zone of mudslides has a more complex origin than that described by Skempton and Petley, and represents the lower part of the moving soil mass, that cannot be associated with the soil below. Figure 4 shows the shear zone found at the base of the Masseria Marino mudslide, along the main track whose slope is around 11°. The top soil under the mudslide body lacks and the shear zone bounds the undisturbed parent formation presumably located under the eroded top soil. The thickness of the shear zone is around 90 cm. It is constituted by a highly remoulded material including lithorelicts.

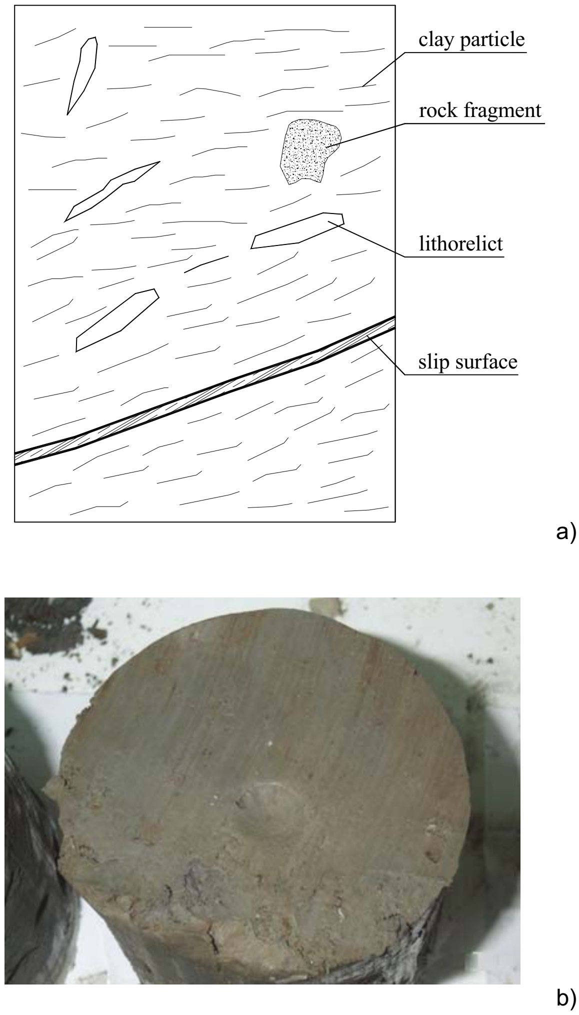

Figure 5. The fabric of a shear zone in highly fissured sheared tectonized clay shales: a) schematic representation; b) a specimen taken from the shear zone found at the base of the Masseria Marino mudslide

According to experience gathered by Neapolitan researchers, as a consequence of remoulding caused by large strains accumulated during movement, the soil in the shear zone is fully softened. It includes a much smaller amount of lithorelicts than the mudslide body (matrix supported fabric), and fissuring is less evident. While a principal shear can be always recognized, often minor shears are not distinguishable with the naked eye. A representation of the fabric of shear zones is reported in Figure 5. These are constituted by a remoulded clay matrix including rock fragments and isolate lithorelicts. A slip surface (or more slip surfaces) is always present. At the micro-scale, the clay particles are essentially aligned in the direction of shear (Guerriero 1995). However, since the shear zone should include also minor shears, clay particles around them can be locally oriented in the same direction as minor shears.

Guerriero (1995) investigated a number of shear zones found at the base of two mudslides in the Basento Valley. Further data regarding shear zones have been collected by Cotecchia et al. (1986), Comegna (2004) and Pellegrino et al. (2004). All investigations have been carried out through pits dug in the main track where the mudslide body is thinner (between 3 and 5 m). The shear zone has been carefully described and the “overall water content” (Hutchinson 1988; Picarelli 1993) measured in the nodes of a grid drawn across the shear zone and in the soil above and below it. In the same nodes the undrained shear strength has been measured with a pocket penetrometer. Finally, samples have been taken for testing in the laboratory.

The thickness of the shear zone recognized in about twenty pits varies between about 5 and 100 cm. The soil is highly remoulded, but some differences in soil fabric can be noticed. In fact, while in some cases the soil is completely destructured and softened, appearing as a homogeneous clay, in other cases some clues of its original fabric can be recognized (softened shear lenses and fissures). However, the water content is always larger than in the mudslide body above, or in the parent formation below. This can be explained by changes of the effective stresses (both normal and deviator) occurred during landslide mobilization (Urciuoli 2002), or by dilation caused by large shear strains induced by movement. Figure 6 reports the overall water content and the shear strength measured in a pit dug within the Masseria Marino mudslide.

The water content distribution within the soil mass is non-uniform. In fact, the liquidity index calculated with reference to the overall water content is rather low (around 0), in contrast with the low strength measured with a pocket penetrometer. Hutchinson (1988) and Picarelli (1993) stress that the water content measured on the soil matrix, i.e. disregarding the contribution of lithorelicts, can be much higher than the overall water content, that includes the contribution of lithorelicts. Data reported by Picarelli (1993) suggest that the liquidity index of the clay matrix can be as high as 1.

Through laboratory triaxial tests carried out on samples taken from either the shear zone or the mudslide body, a few centimetres above the shear zone, Guerriero (1995) obtained the Limit State Surface of soils involved in the Masseria Marino and Masseria De Nicola mudslides. Figure 7 reports the Limit State Surface of the Masseria Marino mudslide. In both cases the size (and maybe also the shape) of the LSS testifies the effects of destructuration and softening occurred within the shear zone. Guerriero (1995) and Comegna (2004) measured the suction induced by sampling: in the hypothesis that suction compares to the field mean effective stress, the soil in the shear zone appears to be slightly overconsolidated.

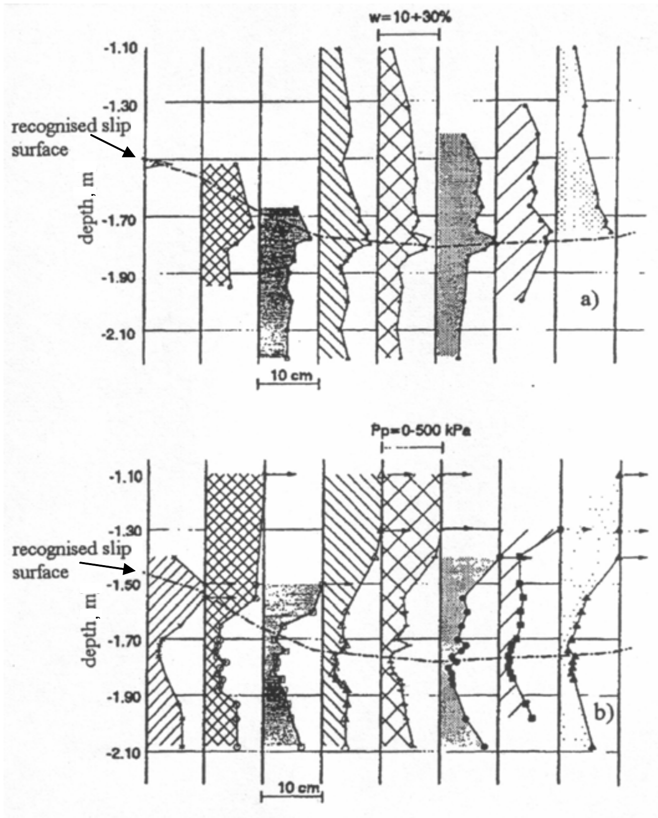

Figure 6. Water content measured in a pit, across the shear zone of the Masseria Marino mudslide (a) and strength (b) measured with a pocket penetrometer (from Picarelli 1993)

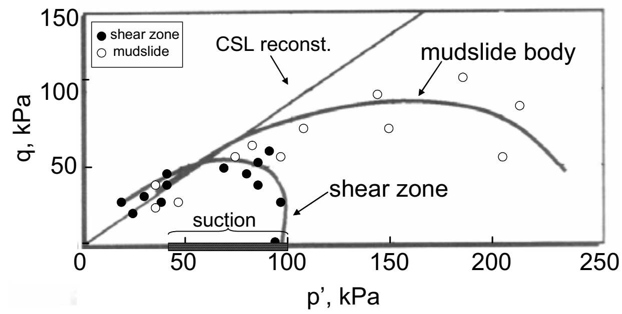

Figure 7. Limit State Surfaces of soils taken from the Masseria Marino mudslide and suction measured in the shear zone (modified from Guerriero 1995)

3. INVESTIGATIONS ON THE SHEAR ZONE OF THE MASSERIA MARINO MUDSLIDE

In the following are reported some results of site and laboratory investigations carried out on the Masseria Marino mudslide. Involved soils are saturated highly plastic silty clays (CF = 40 %; Ip = 27%) whose “overall” void ratio, as discussed above, depends on the soil fabric: its average value is 0.32 in the parent formation, 0.69 in the shear zone and 0.51 in the mudslide body. Laboratory tests have been performed on undisturbed samples taken from pits dug in the landslide body. For comparison, a number of tests have been carried out on reconstituted specimens of the same clay consolidated within a large oedometer. The reconstituted specimens have been prepared mixing clay with distilled water.

Here are reported only the results of permeability and shear strength tests. Data of oedometer and isotropic compression tests are reported by Guerriero (1995) and by Comegna (2004). Further data regarding other mudslides in the Basento Valley are provided by Cotecchia et al. (1986) and by Guerriero (1995).

3.1 Permeability

Permeability has been measured by both laboratory and field tests. Laboratory investigations include falling head tests and constant head tests. In order to investigate the role of soil fabric, the tests have been performed on both reconstituted specimens and undisturbed samples taken from the mudslide body, the shear zone and the parent formation. In the tests on undisturbed specimens, the water flow has been imposed either in the same direction as the slope movement (i.e. parallel to the ground surface) or normal to it (i.e. normal to the ground surface). The falling head tests have been carried out in oedometers, on specimens 20 mm high, with an initial head of about 80 cm: distilled de-aired water has been used. The constant head tests have been executed in triaxial cells on specimens 30 mm high, subjected to a water pressure of 150 kPa at the lower base and of 100 kPa at the upper base: de-aired tap water has been forced through the specimen. Site investigations consisted in falling head tests carried out within some Casagrande piezometers installed in the mudslide, using distilled water.

Figure 8 compares the results of all falling head tests under axial stresses comprised between 50 kPa and 5 MPa. It is worth noting the different void ratios, e, of samples taken from the mudslide body, the shear zone and the parent formation. Despite the different void ratio, the coefficient of permeability, K, of all soils investigated falls in the same range of values, but it is quite lower than the one measured through in situ tests. Notice that the results of field tests have been plotted as a function of the average void ratio measured in the laboratory. However, for a given value of the void ratio, the smallest coefficient of permeability has been measured on specimens of the shear zone, the highest one in the parent formation. An intermediate value characterizes the mudslide body. The permeability of reconstituted specimens is slightly lower than in the shear zone. All tests show a clear linear relationship between the logarithm of the coefficient of permeability and the void ratio, but the slope, C_k, of the straight line fitting data depends on soil. In fact, its maximum value, 0.20, has been obtained on specimens of the shear zone, and the minimum, 0.12, in the parent formation. On soils taken from the mudslide body, it is about 0.17. Once again, the value measured on reconstituted specimens is very similar to that of the shear zone. Finally, the tests highlight that the shear zone is strongly anisotropic, being characterized by a higher value of the coefficient of permeability in the direction of shear than in the direction normal to it and a coefficient of anisotropy around 4. The same is not true for the mudslide body and the parent formation.

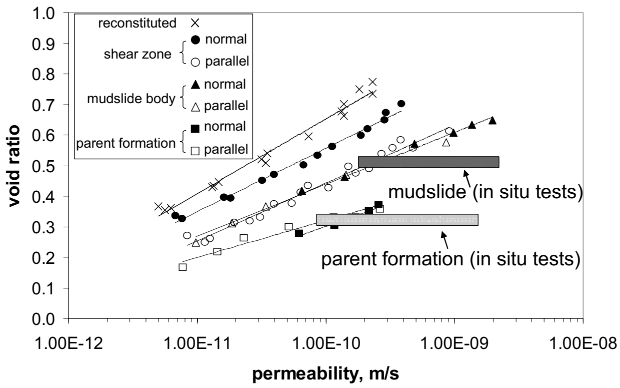

Figure 8. Results of falling head permeability tests

The same general considerations hold for the constant head tests carried out with confining pressures comprised between 80 and 800 kPa, even if in this case a smaller coefficient of permeability has been systematically obtained (Fig. 8). In such a case, the differences in the value of C_k, are even larger than in previous case and the anisotropy of K in the shear zone seems to disappear for a confining pressure larger than 600 kPa.

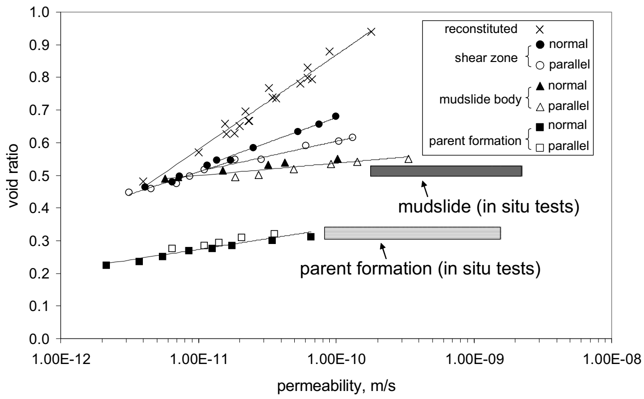

Figure 9. Results of constant head permeability tests

A general interpretation of all test results is quite complicated because of different reasons, as: i) the different experimental procedures adopted (type of equipment, in site and in the laboratory, imposed hydraulic gradients, the different interaction between the water used, tap or distilled water, and the natural pore liquid etc.); ii) some possible experimental mistakes (as it can occur in field tests); iii) the different approaches adopted in the interpretation of test results (in the case of site tests, a boundary value problem must be solved); iv) the incertitude about the exact value of the void ratio of soils around the piezometer cells. However, the soil fabric, at the micro, meso and macro-scale (Dzulinsky 1977; Picarelli 1986) clearly plays a prominent role. The main influent features of fabric are fissuring and particle arrangement. Open cracks (Fig. 3) and minor and principal shears (Figs. 2, 3 and 5) facilitate water movement and affect the coefficient of permeability. The role of cracks and shears in highly fissured sheared clay shales has been already stressed by D'Elia and Palazzo (1994) and by Urciuoli (1994) and is suggested by the comparison between site and laboratory tests and between reconstituted and natural specimens. In particular, it seems minor in the case of the shear zone and significant in the mudslide body and in the parent formation. A similar, even if probably smaller influence on permeability, could be played by lithorelicts in the mudslide body and in the shear zone (meso-scale): in fact, lithorelicts could force water movement inside the clay matrix in the spaces comprised between them (Picarelli et al. 1998). The values of C_k can also be justified by a different role of open discontinuities on soil behavior: in fact, as the state of stress increases, the differences in permeability seem to diminish. Particle arrangement seems to significantly affect the permeability at the micro-scale. In fact, the anisotropy of the shear zone can be explained by orientation of the clay particles; the same can not be observed in the mudslide and in the parent formation. However, constant head tests suggest that the influence of particle orientation decreases with the confining stress, that seems to modify the soil fabric. This effect seems to be smaller in oedometer tests, either for the different induced state of stress or because it is probably masked by some water flow between the specimen and the steel ring; this could also partially explain the differences observed between tests in the oedometer and in the triaxial cell. The anisotropy of permeability induced by shear was investigated by Dewhurst et al. (1996), through tests carried out directly in the annular ring after a annular shear test. Higher values of the coefficient of anisotropy than in the present experience were found.

3.2 Shear strength

The shear strength has been investigated through both drained triaxial and direct shear tests. As for permeability, the tests have been carried out on samples taken from the shear zone, the mudslide body and the parent formation, as well as on reconstituted specimens.

The tests on samples taken from the mudslide body and the shear zone show quite a dilative behavior for confining pressures less than some tens of kPa. Figure 10 reports the Critical State Line obtained from tests on reconstituted normally consolidated specimens and the shear strength measured on samples taken from either the mudslide body and the shear zone. This is systematically higher than the critical strength throughout the investigated stress domain, including the domain of high stresses, where the soil behavior is ductile. Only a few specimens exhibit a strength less than critical.

Additional data regarding the shear zone are shown in Figure 11 reporting the results of direct shear tests. These have been performed either in the same direction as the slope movement or normally to the ground surface. The material exhibits a clear anisotropic behavior up to a normal stress around 150 kPa; above such a stress, a clear distinction between the two testing directions does not seem significant.

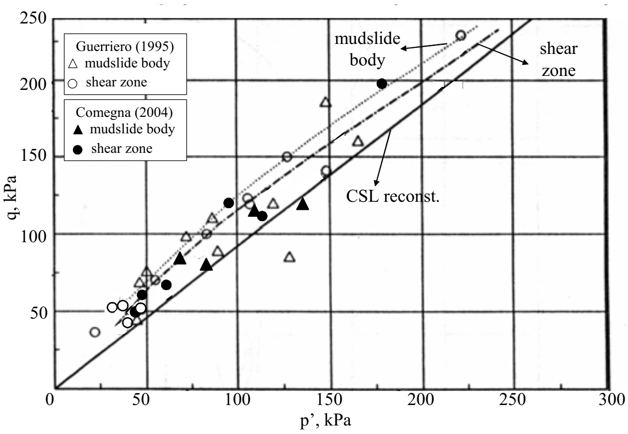

Figure 10. Results of drained triaxial tests on the mudslide body and the shear zone: a) stress-strain curves; b) failure envelopes (modified after Guerriero 1995)

The shear strength measured on samples taken from the parent formation is shown in Figure 12. The results are highly scattered with shear strength values above or below the CSL. Just to try to understand the reason for such difference, in the figure have been sketched the modes of failure of the specimens, whose strength is higher than the critical value (barrel type) and of the specimens having a strength less than critical (shear strain localization). In particular, a barrel type behaviour is associated with a higher shear strength, whereas sliding is manifested by the specimens exhibiting a smaller strength.

All data reported suggest that the soil fabric plays a significant role as on the strength as on the permeability. In fact, as shown by the type of failure recognized in some cases (by sliding), the resistance of the parent formation can be strongly affected by pre-existing principal shears, when unfavourably oriented (Picarelli et al. 1998). In other cases, it is higher , as shown by the different mode of failure (barrel type). Shear discontinuities seem to play a minor role in the case of the mudslide body. In this case, the soil strength could depend on the presence of lithorelicts; these seem to influence the friction angle at constant volume more than the dilation angle. A similar behavior is displayed by the shear zone, unless samples are taken just across the slip surface.

In order to check the last hypothesis, in Figure 13 is reported the large strain shear strength of specimens taken from the mudslide body and from the shear zone. It is very close to the peak strength reported in Figure 10 and still larger than the critical strength. Also at low confining stresses, where the soil behavior is dilative, the large strain failure envelope remains above the CSL. This suggests a "turbulent" response of soil (Lupini et al. 1981), whose strength should depend only on its "index properties", i.e. on its "effective grain size" (Picarelli 1991).

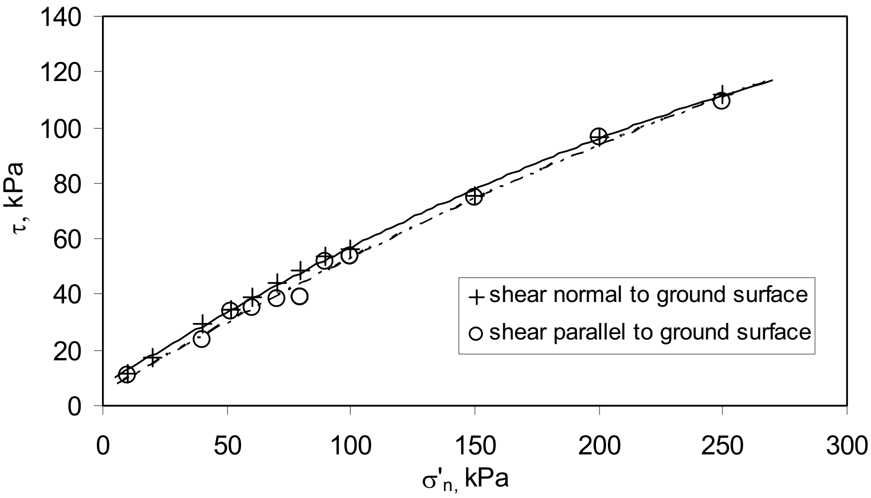

Figure 11. Results of direct shear tests performed on specimens taken from the shear zone

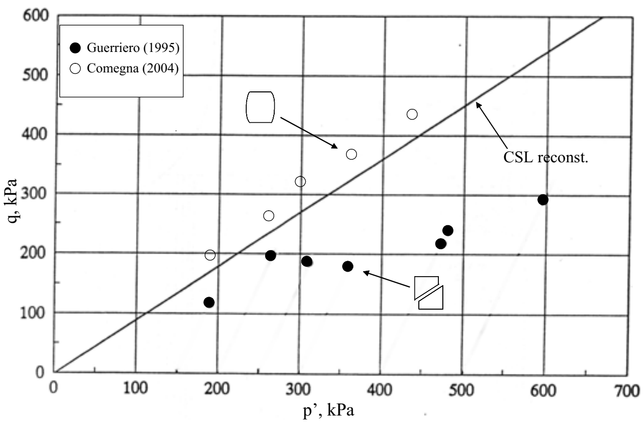

Figure 12. Failure envelope of samples taken from the parent formation

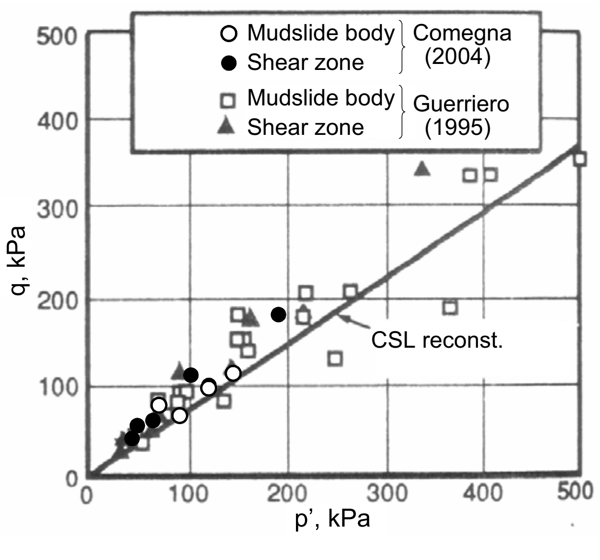

Figure 13. Large strain shear strength of the mudslide body and the shear zone (modified from Leroueil et al. 1997)

4. SUMMARY AND CONCLUSIONS

The Masseria Marino landslide is a typical mudslide in highly fissured tectonized clay shales. Its behaviour is being investigated since long time by researchers of the University of Naples (Iaccarino et al. 1995). As in other cases in the same area (Pellegrino et al. 2004), the mudslide body is constituted by remoulded soils, whose bed (shear zone) is completely destructured and softened as a consequence of movements. Because of remoulding, the fabric of soils owing to the mudslide body is very different from that of the parent formation; strong differences in fabric also exist between the mudslide body and the shear zone.

The role of soil fabric is clearly reflected by the results of laboratory tests. In particular:

- the permeability is higher in the parent formation and lower in the shear zone; an intermediate value has been measured in the mudslide body;
- the permeability of both parent formation and mudslide body strongly depends on the presence of opened cracks and, maybe, principal and minor shears; in fact, the change in permeability with confining stress is higher in these soils than in the shear zone and in reconstituted specimens; also the presence of lithorelicts that force water to flow in the softer clay matrix along paths bounded by them might play a certain role;
- the permeability of the shear zone is close to that of reconstituted specimens; the shear zone is clearly anisotropic as a consequence of the shear-induced fabric, but the degree of anisotropy seems to decrease with the confining stress;
- the shear strength of the parent formation can be strongly affected by the presence of random principal shear surfaces; these seem to be less influent on the strength of the mudslide body and of the shear zone, unless specimens are taken across the slip surface;
- the strength of the mudslide body and of the shear zone seems to be influenced by lithorelicts: these might

cause a “turbulent “ mode of shear and probably affect the friction angle at constant volume;

- the strength of the shear zone is slightly anisotropic as a consequence of its shear-induced fabric.

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