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Main features of mudslides in tectonised highly fissured clay shales

Abstract Mudslides are widespread in the world, especially in areas occupied by highly-fissured plastic stiff clays. Despite their strong impact on structures, infrastructures and, in general, human activity, the knowledge concerning the causes and mechanisms of mudslides is still rather limited. The paper reports some results of long-term research on mudslides in tectonised highly-fissured plastic clay shales carried out through laboratory and in situ tests, monitoring and numerical analyses.

Keywords Highly-fissured clay shale · Mudslide · Monitoring · Mechanisms

Foreword

In Italy, the risk of landslides is very high. In particular, flow-like movements, involving either fractured rock, or granular and fine-grained soils, are widespread. Flow-like landslides generally display quite high displacement rates that cause spreading of the debris very far from the source and high risk for goods located at the foot of the slopes.

Flow-like landslides involving fine-grained soils (mudslides) are essentially concentrated in areas occupied by tectonised, structurally complex formations of marine origin (Urciuoli 1990). These usually include both a lapideous and a fine-grained component. Typically, the fine-grained component is a highly-fissured and sheared stiff plastic clay or clay shale (Esu 1977; Picarelli 1986; Picarelli et al. 1998). The size of these mudslides ranges between tens and hundreds of thousands of cubic metres, but can attain several million cubic metres. Their peak velocity may be of some tens of metres per hour. Mudslides in highly-fissured stiff clays and clay shales have destroyed small towns, viaducts, important roads, and represent a continuous threat for economic and social activities.

Since the end of 1970, researchers of the Università di Napoli Federico II, headed by Arturo Pellegrino, have carried out comprehensive research on mudslides through site and laboratory investigations, monitoring and numerical modelling. The investigated sites are concentrated in the high Basento valley, but the research has been extended to other areas of Southern Italy (Fig. 1), adding sites investigated by the team of the Seconda Università di Napoli. A plan of all investigated sites is presented in Fig. 2. Table 1 lists the investigations carried out at each site, the most significant geometric features of each mudslide and the main references.

The paper gives an overview of the results obtained until the present, and illustrates the future trends of the research that will be pursued even after the sudden loss of professor Pellegrino, which occurred in April 2004.

Mechanisms and style of movement of mudslides in structurally complex formations

Mudslides, as slides, are triggered by mechanisms of shear deformation and rupture. Only in the post-failure stage is the style of movement completely revealed and can be distinguished from that of ordinary slides (Picarelli 2000). In fact, in contrast with slides that move as stiff bodies, mudslides display, or seem to display, temporary deformation patterns similar to those of viscous liquids. As a consequence, at least in some periods of landslide activity, deformation of the entire landslide body seems to predominate over concentrated shear displacements at its base.

Typically, mudslides in highly-fissured stiff clays and clay shales are of the slide–mudslide complex type (Varnes 1978) and include: a source (or alimentation or depletion) area, generally coinciding with the terrace of the slide that causes the mudslide, a track (or more than one track) and an accumulation zone (Fig. 3). However, there are cases in which a true track does not exist and the mudslide spreads over a flat slope.

The depletion area is bounded by the main scarp, which can be as high as some tens of metres. At the foot of the main scarp, the debris of slides that periodically involve the scarp accumulates. Mainly in the case of large mudslides, the morphology of the alimentation zone can be very complex, showing independent smaller slides and small mudslides that occupy the terrace (Fig. 4). After failure, the softened debris of the slides that involve the scarp moves over the terrace of the alimentation zone towards the main track, which often coincides with a pre-existing gully, along which the soil mass can eventually run. Softening can explain the landslide evolution, and the movement of the material, which can easily adjust itself to any change in the cross-section of the track. In particular, the boundary between the terrace and the track typically represents a neck for the soil mass that is discharged from the wider alimentation zone (Fig. 2b).

The debris discharged in the track is conveyed and transported to the accumulation zone. In several cases, various alimentation zones can supply the mudslide body through different tracks (an example is reported below, in Fig. 2c). In active stages of movement, lateral shears can be easily recognised along the boundaries of the track (Fig. 5). This often presents several small steps, constituting secondary accumulations of soil tongues discharged at different times from the alimentation zone (Fig. 2). In active mudslides, either tension cracks (that are open and rather deep) or local thrust shears (that are closed) are present in a direction normal to movement.

The thickness of the mudslide progressively increases from upslope to downslope. The ground surface in the alimentation zone and in the upper part of the track is generally embedded in the slope, whereas the lower part of the track and the accumulation zone rise over the slope surface. In periods of high activity, the track is subjected to some subsidence (Fig. 6) probably caused

Table 1 Investigations, geometrical features and main references concerning mentioned mudslides: L = length; B = width of the main track; D = thickness of the main track; α = average slope

No	Mudslide	Site	Aerial photos	Lab	Monitoring	L (m)	B (m)	D (m)	α (°)	References
1	Brindisi di Montagna	Basento Valley		×	×	700	40	5	10.0	Cotecchia et al. (1984), (1986), Picarelli (1988)
2	Masseria Marino	Basento Valley	×	×	×	370	30	6	10.5	Guerriero (1995), Picarelli et al. (1995), Giusti et al. (1996), Pellegrino et al. (2000), Comegna (2004)
3	Masseria De Nicola	Basento Valley		×	×	1000	20	5	10.0	Guerriero (1995), Giusti et al. (1996), Pellegrino et al. (2004a)
4	Acqua di Luca	Basento Valley		×	×	750	30	3.5	10.5	Giusti et al. (1996), Pellegrino et al. (2004a)
5	Miscano	Miscano Valley		×	×	1000	100	3	9.5	Picarelli et al. (1999)
6	Covatta	Biferno Valley	×	×	×	850	240	12	12	Picarelli (2001), Picarelli and Napoli (2003)
7	Lama del Gallo	Biferno Valley	×	×	×	600	90	12	8.5	Picarelli (2001)
8	Contursi	Sele Valley		×	×	500	70	6	9	Pellegrino et al. (2004b)
9	Quaglietta	Sele Valley	×	×	×	170	200	15	10.5	Di Placido et al. (2004)

by a sort of "stretching" of the soil mass that spreads along the slope, and to erosion of the cap of the stable formation buried under the mudslide body that is "dredged" by movement of the uppermost soil masses (Corominas 1996). This is confirmed by pits dug down to the stable formation which show the complete absence of topsoil (Fig. 10). Observations about the subsidence of the main track in the Brindisi di Montagna mudslide are reported by Cotecchia et al. (1986).

The accumulation zone is generally rather gentle and presents a lobate toe. It can be crossed by thrust shears normal to the movement. In many cases, the accumulation zone spreads over the valley floor which is occupied by a river. This occurred in 1996 in the Biferno Valley (Covatta mudslide), causing the formation of a lake with an impounding larger than one million cubic metres and the collapse of a long viaduct built above the river (Picarelli and Napoli 2003). Fig. 7 reports the stratigraphy of the Sele Valley (Quaglietta mudslide) as obtained by boreholes. As shown by Giusti et al. (1996), this affects the local groundwater flow which is characterised by a strong vertical component.

Mudslides in highly fissured stiff clays and clay shales are often caused by the reactivation of old softened landslide bodies. Mainly in the case of large landslides, reactivation may involve only a part of the landslide body, thus active and non-active parts of the same landslide may be recognised simultaneously. As mentioned previously, mudslides typically represent the evolution of slides, for instance involving portions of the main scarp of a larger landslide.

According to Guida and Iaccarino (1991), the morphological evolution of a single mudslide is characterised by four stages:

- *Stage A*: Quick mobilisation and flow of the soil mass. The landslide surface is highly softened and very irregular, with steps and cracks. The displacement rate ranges between very rapid and moderate (Cruden and Varnes 1996).
- *Stage B*: The landslide flows within well-defined and easily recognisable lateral shears (Fig. 5), but the displacement rate is continuously decreasing, eventually becoming slow.
- *Stage C*: The ground surface is more and more rounded and regular, and the soil body stiffer and stiffer. The geomorphological elements that characterise the mudslide (main and secondary scarps, lateral shears) tend to disappear. The displacement rate is still decreasing, ranging from slow to extremely slow, and the style of movement changes, taking the features of a slide.
- *Stage D*: The landslide body is not easily recognisable on the slope, even through accurate surveys. Movements are extremely slow until a complete stop, which can occur even tens or hundreds of years after mudslide mobilisation.

Mainly in the case of large mudslides, the soil mass can be periodically run by single surges which are discharged by the depletion zone and conveyed in the track. The older landslide body, overloaded by this soil mass, is locally mobilised, but moves with a lower velocity than the uppermost surge. Figure 8 shows an example of surge (lighter in colour) that is being discharged on the accumulation zone (darker in the figure) of a pre-existing mudslide.

Since, in the case of large mudslides, independent movements may develop in the same landslide area, at a given time different parts of the landslide body may display different degrees of ac-

Fig. 1 Mudslides investigated by researchers of the Universities of Napoli. (**1**) Brindisi di Montagna mudslide, Basento Valley; (**2**) Masseria Marino mudslide, Basento Valley; (**3**) Masseria De Nicola mudslide, Basento Valley; (**4**) Acqua di Luca mudslide, Basento Valley; (**5**) Miscano mudslide, Miscano Valley; (**6**) Covatta mudslide, Biferno Valley; (**7**) Lama del Gallo mudslide, Biferno Valley; (**8**) Contursi mudslide, Sele Valley; (**9**) Quaglietta mudslide, Sele Valley

tivity. Figure 4 shows the alimentation zone of the Covatta mudslide (Picarelli 2001) that is occupied by different soil bodies, mobilised in a chain process developed at the time of slope collapse which occurred in April 1996. Figure 9 shows the Brindisi di Montagna mudslide in 1955 and 1980: as clearly shown by the morphological interpretation of the aerial photos, different soil bodies, all located in the same landslide area, display different morphological features, each one associated with different stages of activity.

The main cause of mudslides is rainfall, but the Irpinia earthquake, in 1980, as well as previous less well-documented seismic events, proved that earthquakes represent another fundamental triggering factor. The event of 1980 caused a number of large mudslides (Cotecchia and Del Prete 1984; D'Elia et al. 1985) whose main features were their large size, high peak velocity and a significant time lag between the main shock and the attainment of macroscopic movements (from hours to days).

The Italian literature is rich in examples of mudslides, but well-documented data are quite limited. Regional studies are of primary importance as they provide information regarding homogenous geographic and geomorphological contexts which could be extended to similar geomorphological domains. In this respect, the studies carried out in the high Basento Valley represent a good example (Iaccarino et al. 1995). Other mudslides in

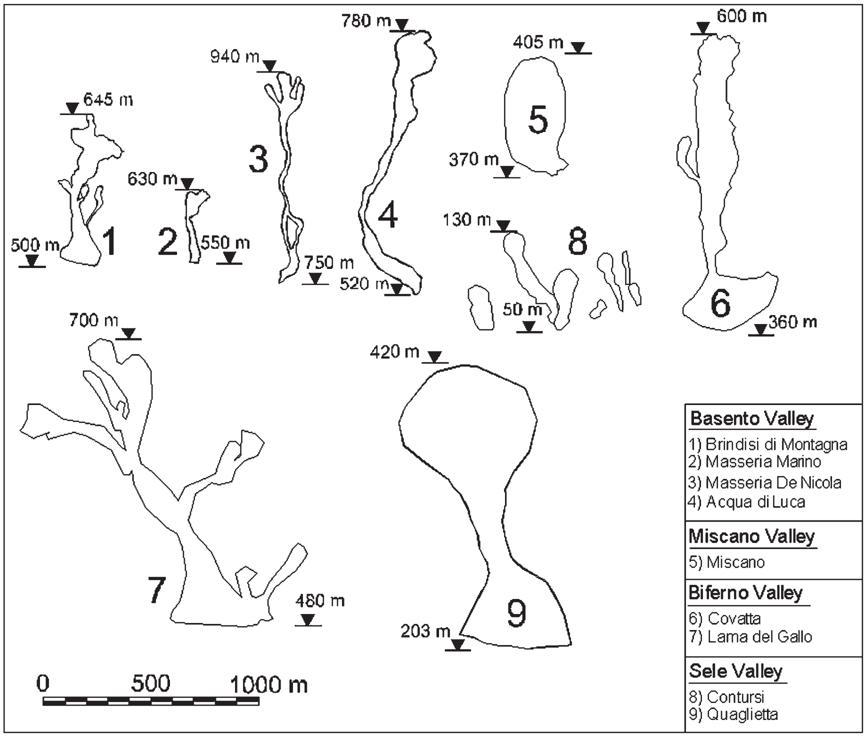


Fig. 2 Investigated mudslides

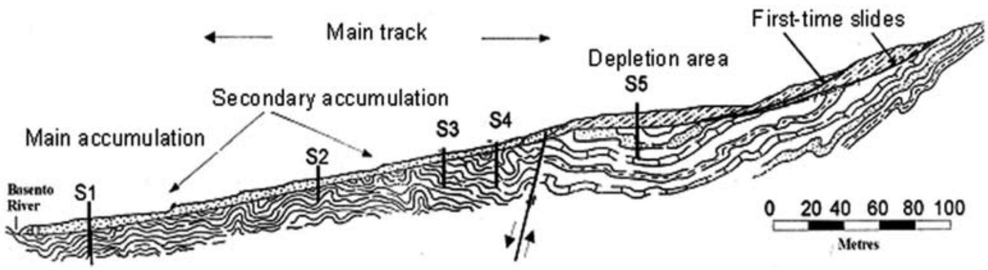


Fig. 3 Cross-section of the Brindisi di Montagna mudslide (from Cotecchia et al. 1986)

very similar materials have been investigated by the researchers of the two Universities of Napoli. In all cases, either laboratory investigations or monitoring through aerial photographs, rainfall gauges, piezometers, topographic measurements and inclinometers, have been carried out (Table 1). In some cases, numerical analyses have been carried out to examine special aspects of the landslide behaviour (Russo 1997; Comegna et al. 2004a).

General features of the mudslide body

Picarelli (1993) described the fabric of mudslide bodies involving highly fissured, stiff clays and clay shales. The debris is composed of clay blocks of the parent formation that have been subjected to a rapid deterioration, and by lapideous blocks and fragments of limestone, sandstone, siltstone or marl, depending on the nature of the parent formation. These clayey and lapideous blocks have been plunged into a softened, fine-grained matrix. This consists of a mixture of clay and centimetre to millimetre-sized hard lumps (lithorelicts). Similar remarks about the features of the clay matrix are reported by other authors (Skempton and Huchinson 1969; Brunsden 1984; Vallejo 1989).

The clay matrix appears quite soft, even though its liquidity index based on measurements of the "overall" water content (Hutchinson 1988) is generally high, typically around one. This

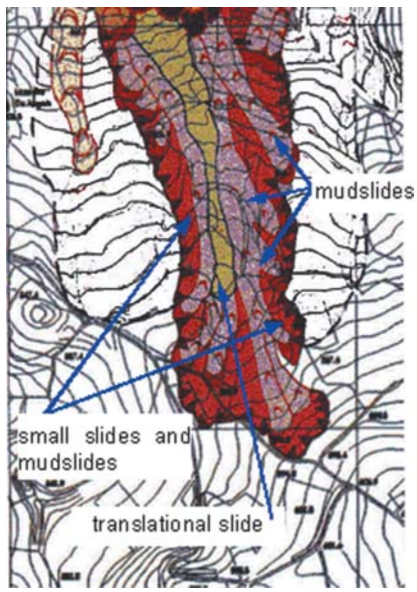


Fig. 4 Alimentation zone of the Covatta mudslide (from Picarelli 2001)

Fig. 5 Lateral shear along the left boundary of the Masseria Marino mudslide

Fig. 6 Lateral shear of the Masseria Marino mudslide highlighted by the subsidence of the main track

apparently strange result depends on the low water content of the lithorelicts contained in the matrix, that affect the overall water content. In fact, if they are separated from the remaining part of the matrix, a higher value of the water content and of the liquidity index can be obtained (Hutchinson 1988). Using data concerning four mudslides in the Basento Valley, Picarelli (1993) shows that the liquidity index of the "general" matrix, obtained by eliminating all the fragments whose size is larger than 2 mm, can be even higher than one.

The lower part of the mudslide body is composed of a completely remoulded shear zone having a thickness between a few centimetres and one metre (Guerriero 1995; Comegna et al. 2004b), including principal and minor shears; often, the minor shears are not recognisable to the naked eye. The material of the shear zone has completely lost its original fabric, appearing as a homogeneous clay with only isolated and very small clay lumps and rock fragments. Especially in the track and in the accumulation zone, the shear zone is directly superimposed on the fresh parent formation, the top soil of this having been completely eroded during movement.

Figure 10 presents some examples of shear zones investigated through pits dug down to the underlying stable formation. The contrast between the shear zone and the mudslide body or the parent formation, above and below it, respectively, is always clear.

Figure 11 gives the "overall" water content measured along some vertical sections drawn across the shear zone of the Masseria Marino, Masseria De Nicola and Miscano mudslides. In the same figure, the undrained shear strength measured with a pocket penetrometer is also shown. The shear zone is easily revealed by the higher value of the water content and the smaller shear strength, that attains its minimum value close to the slip surface.

The main features of highly-fissured clay shales involved in mudslides (the parent formation) have been discussed by Picarelli et al. 1998, 2002. In particular, they have stated that these geomaterials present:

- a complex structure characterised by an intricate set of closely-spaced polished or slickensided fissures that subdivide the material into small indurated platy fragments (Fig. 10 and 12) and affect both the stiffness at medium to high strains and the shear strength;
- a strong susceptibility to softening, provoked by stress release and absorption of water; this causes a quick change of soil structure characterised by a progressive obliteration of fissures; in the long-term, the soil turns into a homogenous apparently non-fissured clay.

Di Maio (1996) showed that the nature of the liquid supplied to the soil during swelling may have a direct influence on its behaviour. In fact, volumetric strains are much larger when the soil is exposed to distilled water than to salt solutions. In the light of such results, Picarelli et al. (1998) suggest that softening exhibited by sheared highly-fissured clay shales can be a consequence of adsorption of fresh water (such as rainwater) following stress relaxation phenomena occurring as a consequence of slope failure and soil movement. This could partially explain the special fabric of the debris constituting the mudslide body.

Fig. 7 Cross section of the Quaglietta mudslide (from Di Placido et al. 2004)

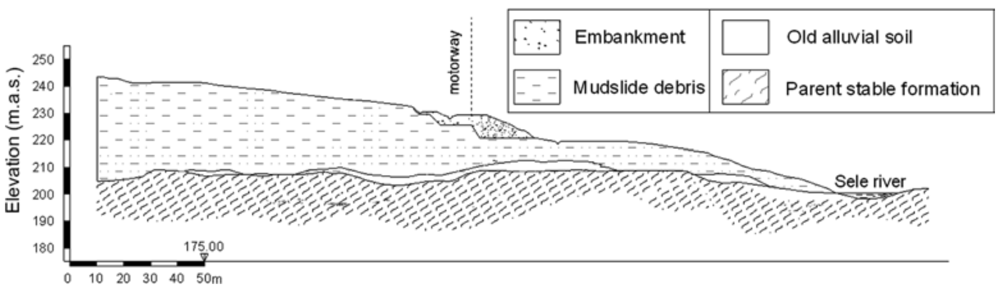


Fig. 8 Spreading of debris over the accumulation zone of a mudslide in the Biferno Valley (from Picarelli 2001)

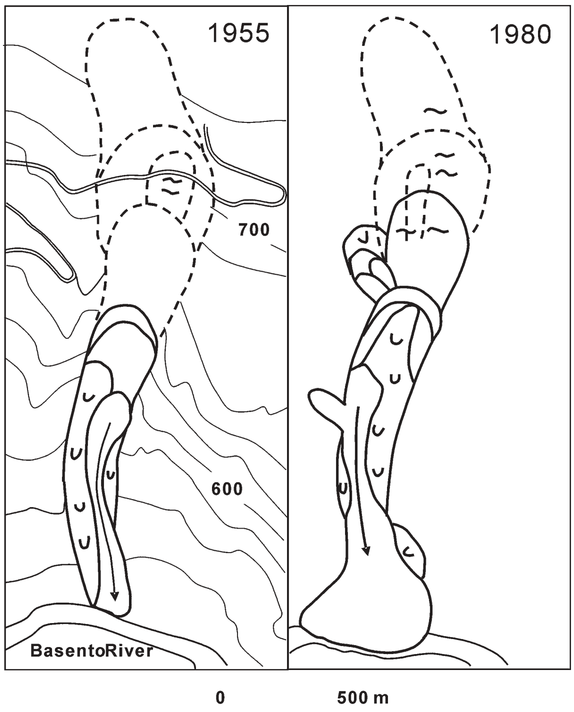


Fig. 9 The Brindisi di Montagna mudslide as shown by aerial photographs taken at different times (from Iaccarino et al. 1995)

Such a fabric affects the soil behaviour and its mechanical properties. Tests carried out by Guerriero (1995) and Comegna (2004) stress the high compressibility and the contractive behaviour, when subjected to shear stresses, of samples taken from the mudslide body. This is due to the influence of the clay matrix which governs the soil behaviour. More details about the properties of soils involved in mudslides are reported by Guerriero (1995), Guerriero et al. (1995) and Comegna (2004).

An important part of the research on mudslides has been dedicated to the investigation of the hydraulic and mechanical properties of soils within the shear zone (Guerriero 1995; Comegna 2004; 2004b).

Despite the nature of the parent formation, the soils of the shear zone appear to be only slightly overconsolidated. Figure 13 reports the Limit State Surface of samples free of shear discontinuities, taken from the shear zone of the Masseria Marino mudslide, at a depth of slightly less than 3 m. It is much smaller than the Limit State Surface of samples taken, more or less at the same depth, above the shear zone, and seems to reveal some anisotropy. Also, on the p' axis, the figure reports the suction measured, on perfectly saturated samples, by the method proposed by Bishop et al. (1975). Assuming that the suction represents the average field effective stress, its vicinity to the isotropic yield stress suggests that the shear zone is nearly normally consolidated. The results of oedometer and CID triaxial tests are in quite good agreement with previous considerations (Guerriero 1995; Comegna 2004). Similar information can be gleaned from the results of tests carried out by Cruden et al. (1975) on the shear zone of a ice-thrusting clay shale formation near Edmonton, Alberta.

A series of tests were carried out in order to check if shear stresses affecting the shear zone are responsible for soil anisotropy. To this aim, a number of specimens were taken in the same direction as the slope movement and in the direction normal to it, then they were subjected to permeability and direct shear tests. All tests clearly showed the anisotropic nature of the shear zone whose permeability and strength in the direction of movement are always higher and smaller, respectively, than in the direction normal to it (Fig. 14). This has to be related to the induced microfabric, which is featured by clay particles oriented in the same direction as shear. From collected data, it can be argued that the entire shear zone, whose thickness may reach one metre, is anisotropic.

Finally, it must be remembered that the shear zone includes several minor shears and one or more principal shears (slip surfaces) that control the landslide behaviour. Tests carried out by Picarelli (1986), on samples carefully taken across the slip surface, and by Comegna (2004), on specimens including minor shears, show that the strength operative along these discontinuities is equal or close to the residual shear strength measured with conventional direct shear tests.

Groundwater regime

All mudslides listed in Table 1 are equipped with piezometers installed either in the landslide body or in the stable formation below it. All data show that the groundwater regime in the mudslide body is very sensitive to rainfall recharge. Permeability tests carried out in boreholes in the Masseria Marino and Masseria De Nicola mudslides demonstrate that the hydraulic conductivity of the soil mass is larger than that of the lower stable formation (Urciuoli 1994; Picarelli et al. 1998). Probably the field conductivity is still larger, as a consequence of the continuous opening of cracks during movement. In addition, the depression produced by the presence of the landslide in the slope facilitates infiltration, that is supplied by run-off conveyed from upslope. It is worth noting that the subsidence of the track caused by erosion of the basal surface (Corominas 1995; Bromhead and Clark 2004) enhances the development of a depression in the slope. As a consequence of this morphological situation, the landslide body behaves as a sort of water reservoir.

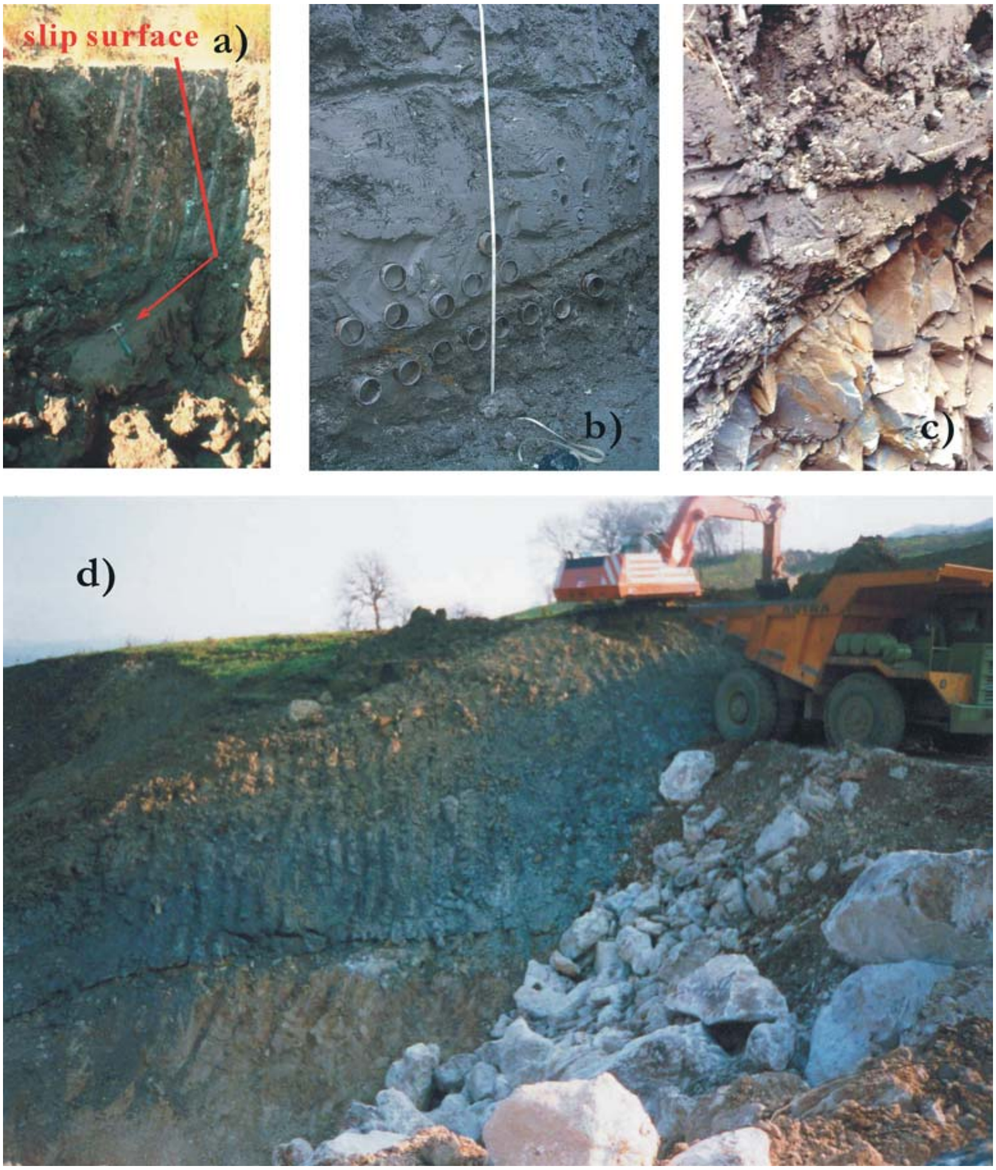


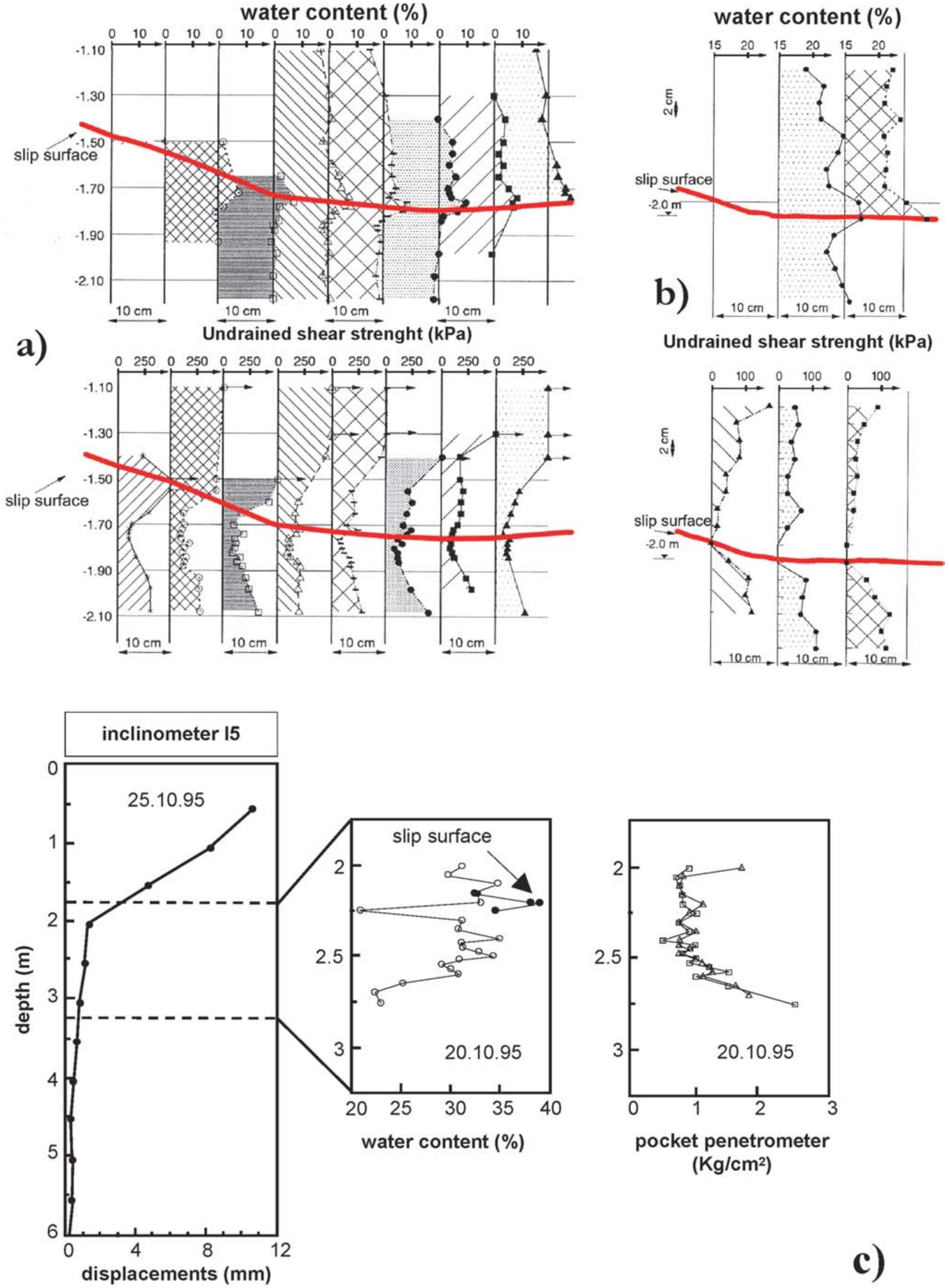
Fig. 10 Examples of shear zones at the base of mudslides: (**a**) Brindisi di Montagna mudslide (Picarelli 2001); (**b**) Masseria Marino mudslide (Comegna et al. 2004b); (**c**) Masseria De Nicola mudslide (Picarelli 2001); (**d**) Quaglietta mudslide (Di Placido et al. 2004)

In order to discuss the groundwater regime, it is useful to refer to slow mudslides (stages C and D) whose pore pressure field is not affected by movements. In fact, as will be shown below, pore pressures acting in rapid and moderate mudslides (stages A and B) could not be in equilibrium with hydraulic boundary conditions, as a consequence of changes of the total stress field associated with slope movements.

Figure 15 shows the seasonal fluctuations of the water level in the extremely slow Acqua di Luca and Contursi mudslides, over a period lasting more than ten years (Pellegrino et al. 2004b, c). Similar data have been obtained in other slow landslides (Picarelli et al. 1999). Typically, the pore pressure attains its peak value in the period December–April, then gently decreases reaching a minimum between October and December. In the dry season between May and November, even intense rainfall does not produce significant increases of pore pressures, probably because of evapotranspiration and of the lower permeability of the shallowest unsaturated soil layers.

Comegna et al. (2004a) set up a simple model to reproduce the pore water fluctuations caused by rainwater infiltration in a non-active portion of the Masseria Marino mudslide using data provided by a rainfall gauge installed on the slope and accounting for the permeability measured by in situ tests. The agreement between measured and calculated values is good (Fig. 16a). The same cannot be said for the active zones, where the displacement rate is quite high (Fig. 16b). In these zones the adopted model cannot reproduce the measured values due to the development of excess pore pressures (see next section).

Referring to extremely slow mudslides, the water flow usually has a significant vertical component toward the base of the landslide body and the underlying stable formation due to infiltration from the ground surface (Fig. 15). A similar consequence may result from the presence of highly pervious alluvial soils present below the accumulation zone, that often spread over the bed of a creek or river (Fig. 7). This situation has been checked by an analysis of piezometer measurements carried out in the ac-



water content (%)
slip surface
10 cm
a)
Undrained shear strenght (kPa)
water content (%)
2 cm
slip surface
-2.0 m
b)
10 cm
Undrained shear strenght (kPa)
inclinometer I5
25.10.95
depth (m)
displacements (mm)
slip surface
20.10.95
water content (%)
20.10.95
pocket penetrometer
(Kg/cm²)
c)

Fig. 12 The Brindisi di Montagna highly-fissured clay shale (from Picarelli et al. 1998): (**a**) parent flysch formation; (**b**) fine grained component

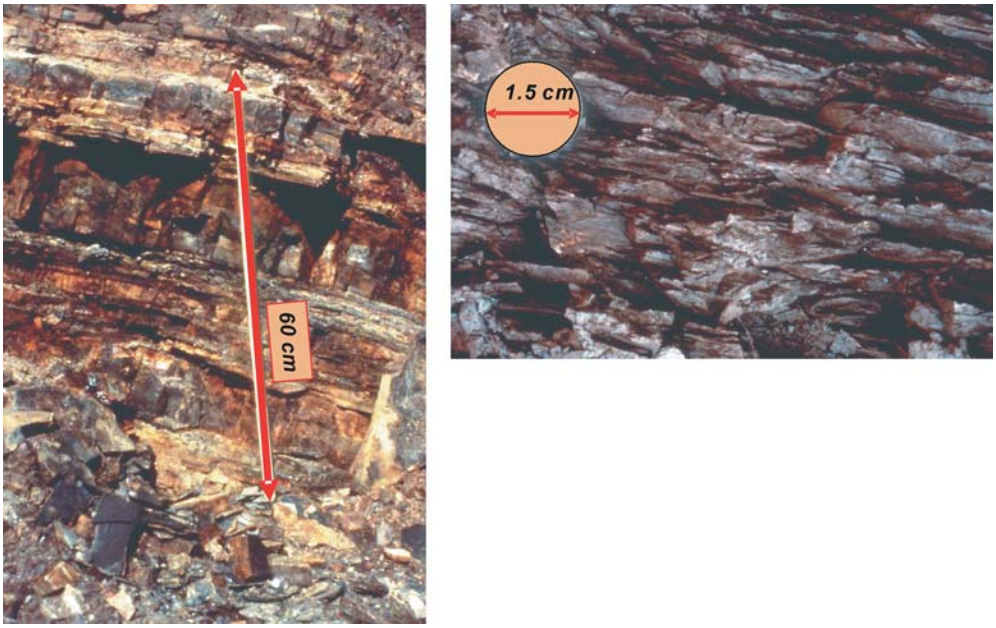
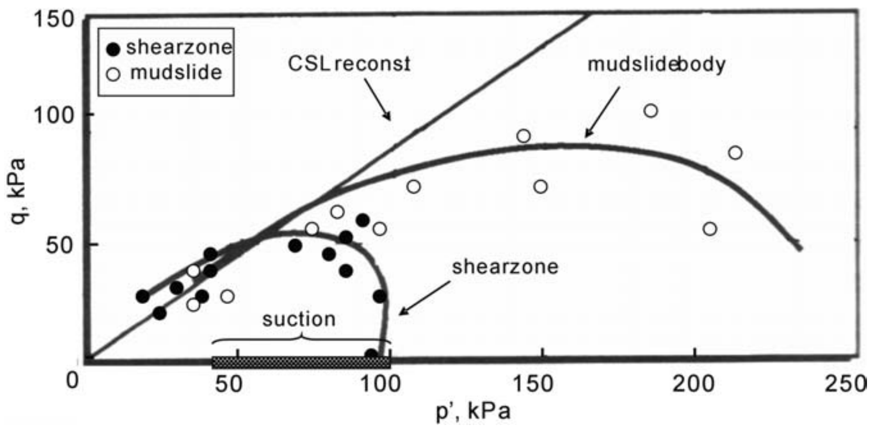


Fig. 13 Limit State Surface of the shear zone of the mudslide body obtained on samples taken at a similar depth in the Masseria Marino mudslide (modified after Guerriero 1995)



cumulation zone of the Masseria Marino mudslide (Giusti et al. 1996).

It is worth mentioning that the direction of water flow affects the safety factor. This can explain why the mobilised friction angle calculated in the ordinary assumption of flow parallel to the ground surface is generally higher than the residual friction angle. In mudslides investigated in the Basento Valley, the vertical hydraulic gradient is typically about 0.3, that is twice the gradient measured in the slope direction. In this way, the pore pressure under the water table is equivalent to a water column of $0.7z_w$, where z_w is the vertical depth from the water table. For $c'=0$, this implies that the safety factor is some 30% larger than in the assumption of flow parallel to the ground surface. Similar considerations are reported by Bertini et al. (1993).

Fig. 11 Water content and undrained shear strength measured across the shear zone reached through some pits: (**a**) Masseria Marino mudslide (from Guerriero 1995); (**b**) Masseria De Nicola mudslide (from Guerriero 1995); (**c**) Miscano mudslide (from Picarelli et al. 2004)

Some remarks about the mechanics of mudslides

Mudslides in highly-fissured clay soils may be active for a very long time. Iaccarino et al. (1995) report that some mudslides in the Basento Valley have been active for hundreds of years; similar data are reported by other authors. However, detailed information is scarcely available for such long periods of time; only some assumptions can be made using data collected over much shorter periods of time. Iaccarino et al. (1995) report that the displacement rate may display strong temporary variations; sometimes quiescent mudslides are subjected to a sudden dramatic reactivation; this occurred in 1996, in the Biferno Valley, where the huge Covatta mudslide was reactivated (Picarelli and Napoli 2003).

Figure 17 reports the evolution of the displacement rate of three mudslides in the Basento Valley. The figure shows peaks due to landslide acceleration, every peak being followed by a slow decrease in the displacement rate. In the long term, this may decrease to a few millimetres per year. Therefore, the landslide may experience, more than once in its life, all the geomorphological stages described above.

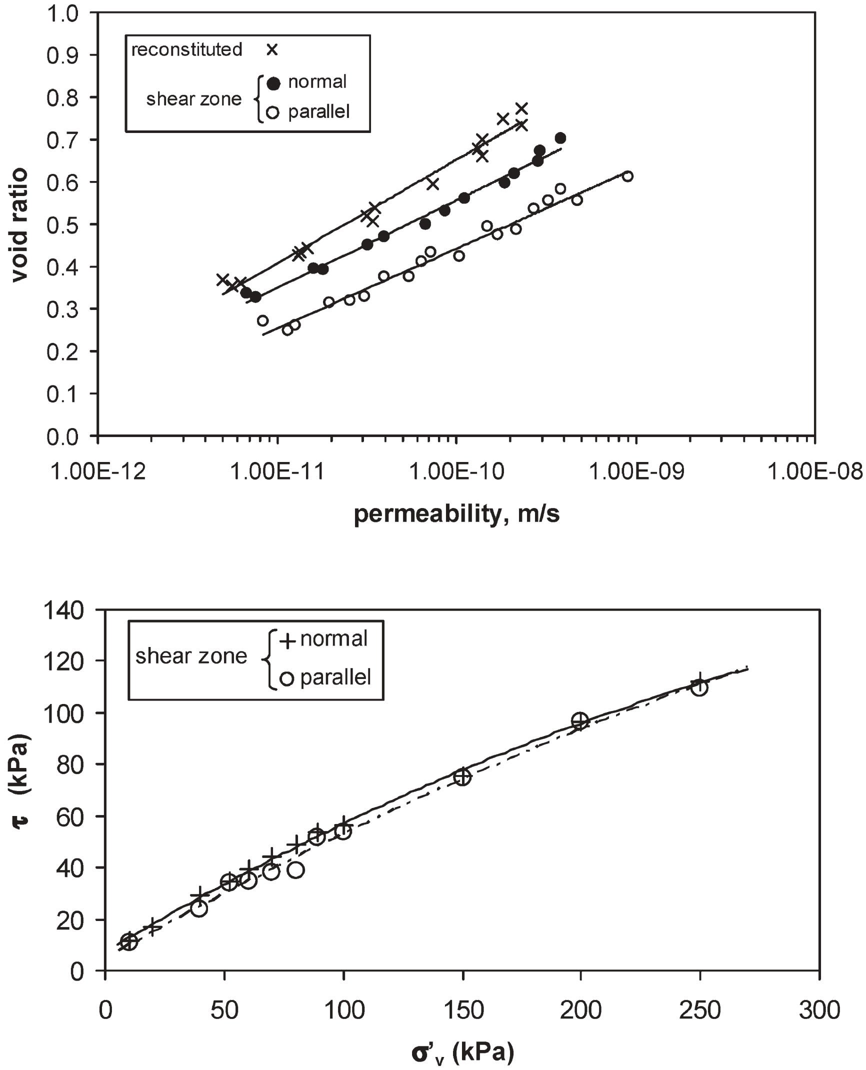


Fig. 14 Results of tests aimed at investigating the anisotropic nature of the shear zone (from Comegna et al. 2004b): (**a**) permeability; (**b**) shear strength

Unfortunately, data about the peak value that can be attained by the displacement rate are scarce because of the difficulty to rapidly install any type of instrumentation. In addition, even when already present, instruments are rapidly destroyed by movement. A velocity larger than a hundred metres per day has been estimated for mudslides triggered by the Irpinia earthquake (D'Elia et al. 1985; Picarelli 2001). A couple of years after the slope collapse, induced by a continuous rainfall in April 1996, the Covatta mudslide displayed a velocity still larger than several decimetres per hour (Picarelli and Napoli 2003). Seven years after its presumed reactivation, the peak velocity of the Brindisi di Montagna mudslide was still around 18 m per month (Cotecchia et al. 1986). Further data regarding structurally complex clayey soils are reported by other authors (Giusti et al. 1996).

All available data indicate that the different geomorphological stages described above can be characterised by different drainage conditions. As suggested by the same curve of displacements with time, very similar to a consolidation curve (Fig. 17), Picarelli (1988) assumed that in the initial stage of movement the soil mass is subjected to an undrained state of stress, followed by a progressive dissipation of excess pore pressures. It is worth noting that the high plastic strains induced in the mudslide body as a consequence of excess pore pressure generation can justify the typical pattern of movement exhibited by mudslides. However, probably a succession of partially undrained and drained stages, associated with changes of the displacement rate, is a more realistic (and complex) interpretation of the soil behaviour. The results of pore pressure measurements provide a support to these considerations.

Figure 18 summarises the behaviour of the Masseria Marino mudslide investigated from the middle of 1991 to the end of 1993. Water levels measured with Casagrande piezometers in the zone between the depletion area and the upper part of the main track showed quite irregular changes over short periods of time (Fig. 18b). However, as displacements accelerated (Fig. 18c), the water level rose above the ground surface as a likely effect of induced excess pore pressures. It is worth noting that the investigated zone was clearly subjected to some compression, as revealed by topographic measurements (Fig. 18a).

Since Casagrande piezometers are not able to capture water levels above the ground surface (as shown in Fig. 18b), some vibrating wire piezometers with automatic pore pressure recording devices were subsequently installed in the same area. Figure 19 reports the horizontal displacement of the ground

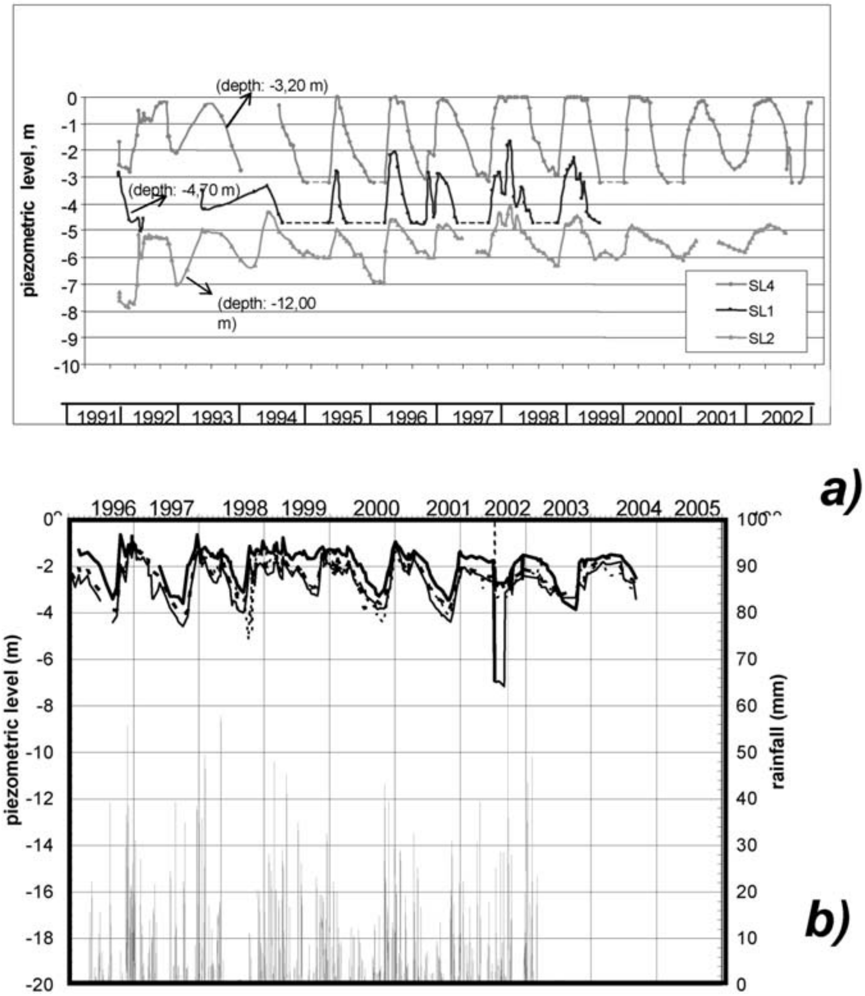


Fig. 15 Water levels measured with Casagrande piezometers in the Acqua di Luca (**a**) and Contursi (**b**) mudslides (from Pellegrino et al. 2004b, c)

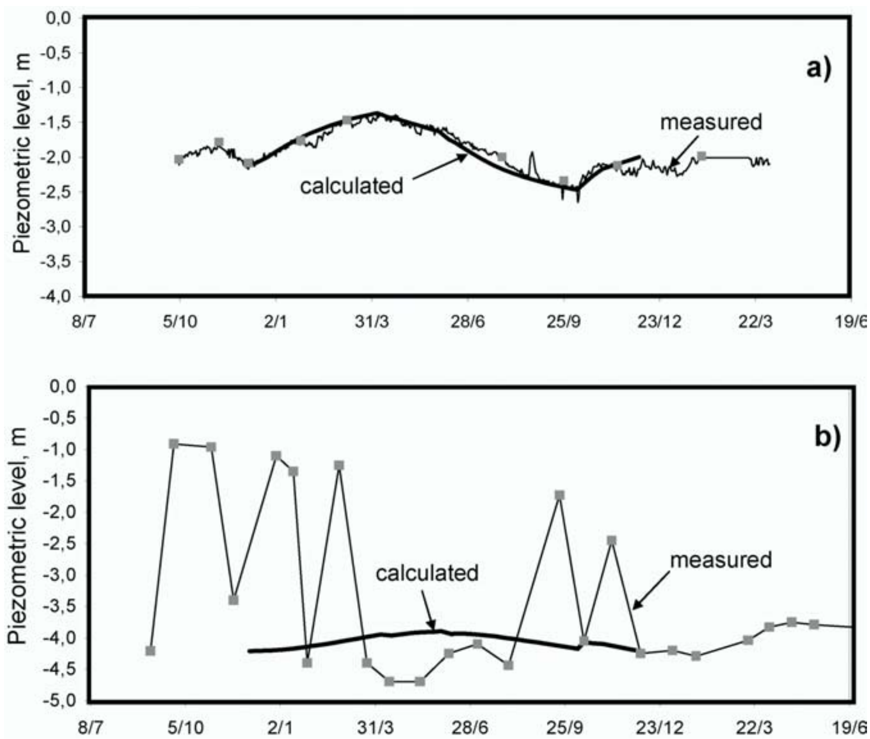


Fig. 16 Comparison between measured and calculated groundwater levels in a non-active (**a**) and in an active part (**b**) of the Masseria Marino mudslide (from Comegna et al. 2004a)

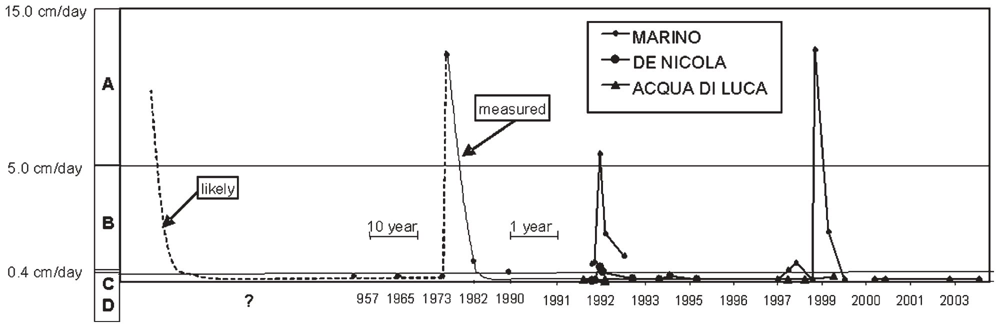


Fig. 17 Displacement rates of three mudslides in the Basento Valley (from Pellegrino et al. 2004a)

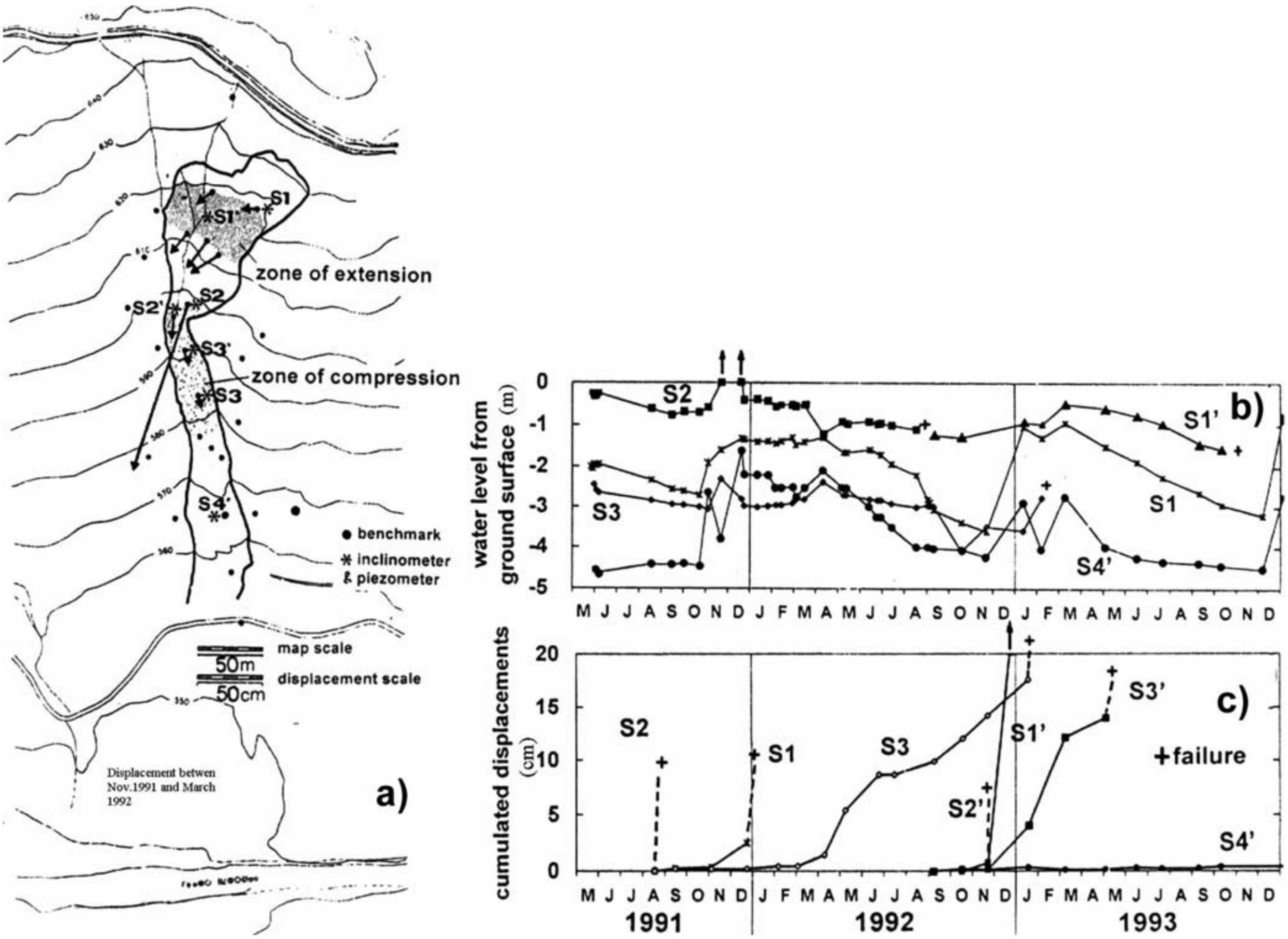


Fig. 18 Displacements and water levels measured in the Masseria Marino mudslide in the period 1991–1993 (from Giusti et al. 1996): (**a**) plan of the landslide and surficial displacements; (**b**) water levels measured at some Casagrande piezometers; (**c**) evolution with time of horizontal displacements

surface and the piezometric level measured at a depth of 3 m, about 3 m above the slip surface, for the period 1995–1998. Once again, the mudslide acceleration is associated with a building up of the pore pressure, corresponding to an increase of the water level to almost 3 m above the ground surface. In particular, such readings definitely demonstrate that: (i) excess pore pressures can develop not only at the base of the mudslide, but also within its body; (ii) the pore pressures can attain a peak value very close to the total stress, causing a strong decrease in the effective stress.

As shown by Fig. 16b, these pore pressures cannot be justified simply by accounting for infiltration following rainfall, as for slow landslides (Fig. 16a), since they are probably caused by changes in the total stress which are faster than the time required for pore pressure equalisation: this can be easily explained by the low soil permeability.

Fast changes of the internal state of stress can be due to different mechanisms, all quite usual in mudslides (Picarelli 2001):

(a) static loading caused by accumulation of debris discharged on the mudslide body from the main or secondary scarps (Hutchinson and Bhandari 1971);

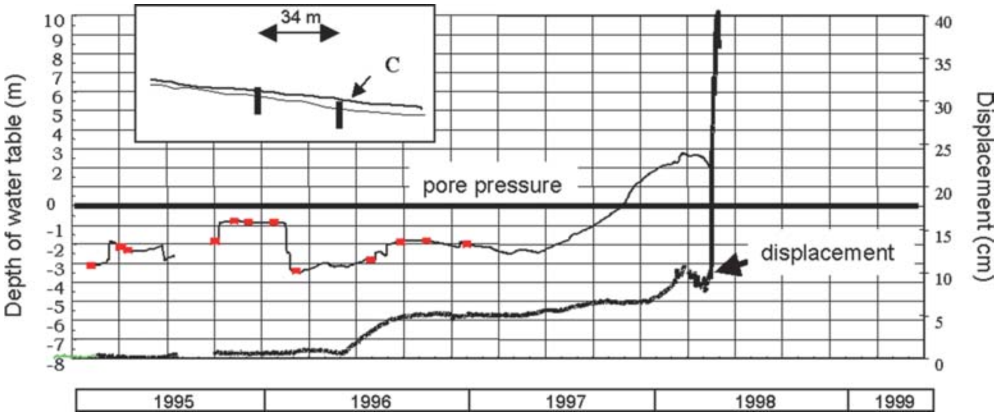


Fig. 19 Horizontal displacements and piezometer levels in the Masseria Marino mudslide in the period 1995–1998 (from Pellegrino et al. 2004c)

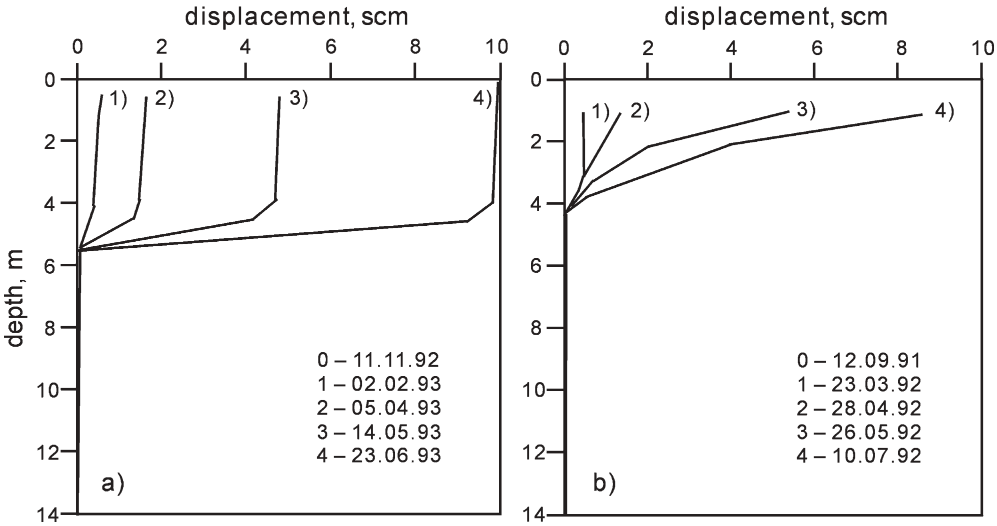


Fig. 20 Inclinometer profiles in two mudslide of Basento Valley (from Picarelli et al. 1995): (**a**) stage of slow movement (Masseria De Nicola mudslide); (**b**) stage of quite rapid movement (Masseria Marino mudslide)

(b) quasi-static loading caused by surges travelling over the landslide body as in Fig. 8 (Vallejo 1984);
(c) compressive deformation associated with differences in resisting forces mobilised along the boundaries of (d) the mudslide body, because of differences in soil properties, or variation of the slope of the slip surface, or variations in pore pressures, or lateral restraints, as in the neck present between the depletion zone and the track (Picarelli and Russo 2004);
(d) effects of seismic (cyclic) loading, as in the case of mudslides induced by earthquakes.

Pellegrino et al. (2004c) show that accumulation of debris at the foot of the main scarp may be interpreted as a rapid sedimentation phenomenon causing a building up of excess pore pressures not only in the subsoil (mechanism as mentioned above), but also in the same sedimented materials under its own weight: as a consequence, this can turn into a fast surge travelling over the pre-existing landslide (mechanism b). Also, reactivation of old gentle landslide bodies may cause a building up of excess pore pressures as a consequence of redistribution of the internal state of stress (mechanism c). In addition, as shown above (Fig. 18), excess pore pressures can be locally induced by compression of the mudslide body due to loading caused by a surge or by lateral restraints associated with the presence of a neck along the slope (mechanism c). Finally, experience such as that gathered during the Irpinia earthquake suggests that mudslides can be provoked by cyclic loading caused by ground motion (mechanism d).

Unfortunately, as for pore pressures, data regarding the mechanisms of deformation of mudslides are scarce, mainly for the very first stage of movement. It many cases it can be argued that, after triggering, the soil mass starts moving as a viscous fluid, even though in the last phases of movement the mechanism of deformation seems to turn into that of a slide. Figure 20 shows two inclinometer profiles recorded in two mudslides of the Basento Valley, the first one in a phase of slow movement (Masseria De Nicola) and the other one in a phase of quite rapid movement (Masseria Marino). In the first case, shear strains are significant only in the shear zone located at the base of the mudslide, while in the second one they are quite large all over the landslide thickness. The boundary conditions, soil properties and drainage conditions are all fundamental factors in controlling the mechanisms of deformation (Picarelli et al. 1995). However, as mentioned before, in the very first stages of movement large internal deformation of the mudslide body could be caused by the development of plastic shear strains involving the entire soil mass as a consequence of excess pore pressures; in the last stages of movement, when pore pressures decrease to smaller values in equilibrium with hydraulic boundary conditions, only the shear zone seems to experience large shear strains induced associated to sliding along the slip surface.

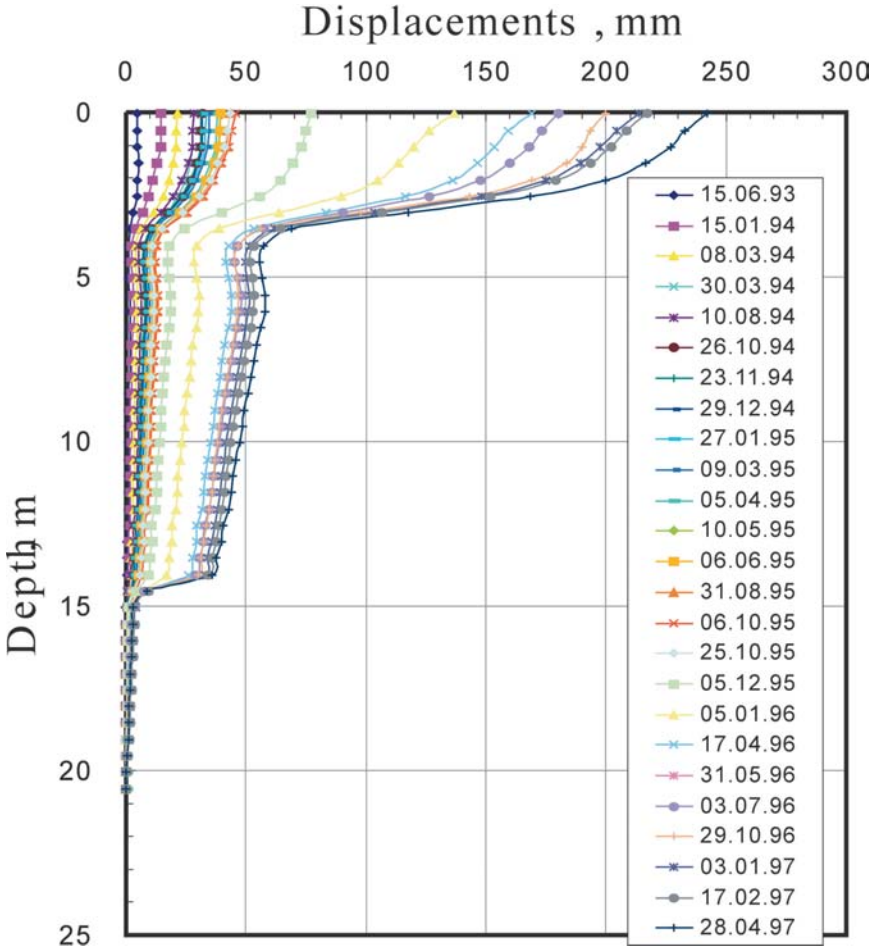


Fig. 21 Inclinometer profiles in the Miscano mudslide (from Pellegrino et al. 2004c)

Finally, a special situation already mentioned before is shown in Fig. 21. This depicts the movement of two independent, superimposed soil masses characterised by both a different velocity and a different mechanism of deformation. In fact, while the upper soil mass experiences diffuse and larger shear strains, the lower one moves as a stiff body over a slip surface. This can occur when a faster mudslide (surge) travels over the main landslide body.

Short conclusions

Mudslides are widespread in highly-fissured plastic clays and clay shales of the Italian Apennines. The high susceptibility of these formations to softening is certainly one of the reasons for the development of flow-like landslides.

Several mudslides have been investigated in detail by researchers at the two Universities of Napoli. Laboratory testing and in situ investigations including monitoring, provided much useful data for the analysis of the mechanisms of mudslide triggering.

The fabric of the mudslide body presents special features that have significant effects on soil properties and behaviour. At the base of the mudslide a slightly overconsolidated shear zone, where high shear strains develop, is always present, affecting the landslide behaviour.

Mudslides can be active for decades, but their evolution displays strong changes of both geomorphological and kinematic features. In particular, strong changes of the displacement rate are induced by changes of boundary conditions caused by varying alimentation conditions, rainfalls or earthquakes. In particular, the stages of high velocity seem to be associated with the establishment of undrained or partially undrained conditions, that are responsible for generation of excess pore pressures and of the large shear strains that affect the soil body. The following dissipation of excess pore pressures is associated with the decrease of the displacement rate and the changing pattern of slope movement.

The continuation of the research will include further studies about the mechanisms of softening, the properties of the shear zone and the mechanics of movement, thus supplying new data which is useful for the prediction of the behaviour of mudslides and risk mitigation. Collaboration with other researchers engaged in similar investigations would be welcome.

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