Discussion

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Discussion to "Evolution of shear-zone structure in undrained ring-shear tests" by M.W. Agung, K. Sassa, H. Fukuoka, and G. Wang [*Landslides* 1(2):101–102, July 2004]

Through a careful examination of the fabric of reconstituted samples of silica sand subjected to undrained ring shear tests, the authors describe the main features of shear zones generated by very large and fast displacements in saturated granular soils. Such investigation provides new insights into the changes in soil fabric induced by fast shearing.

The paper shows that undrained shearing leads to a progressive increase in the thickness of the shear zone, grain crushing, and significant changes in soil fabric. After an initial stage during which the soil response to imposed deformation and associated excess pore pressure is quite complex, the soil fabric becomes more and more uniform. In particular, the undulating shear fissures formed just after peak tend to progressively disappear with deformation. At the same time, local soil compaction and grain size segregation lead to formation, within the shear zone, of an internal core constituted by well-aligned particles, which is denser and coarser than the soil around it. This process seems to complete itself only when the steady-state condition is attained.

Parallel considerations could be made for shear zones in clay, even if well-documented data miss concerning saturated specimens subjected to large displacements under undrained shearing. However, these conditions seem to apply to shear zones located at the base of mudslides (Picarelli et al. 2005). In fact, mudslides typically experience very large displacements (up to hundreds of meters), and many clues suggest that excess pore pressures can build up, especially in stages of mudslide triggering or acceleration (Picarelli 1988; Pellegrino et al. 2004; Comegna et al. 2004a).

Fig. 1 Examples of shear zones: **a** shear zone exposed in a pit (from Pellegrino et al. 2004); **b** sample taken from the mudslide body above a shear zone (from Comegna et al. 2004b); **c** sample taken from a shear zone (from Comegna et al. 2004b); **d** sample taken from the parent formation below a shear zone (from Comegna et al. 2004b)

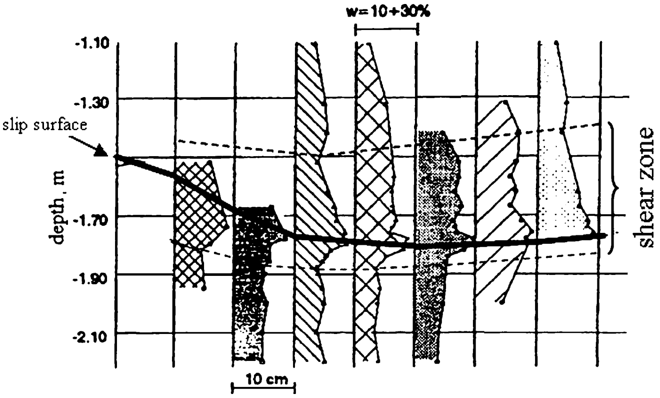


Fig. 2 Water content profile measured in a pit dug through a mudslide body down to the parent formation overlain by the shear zone (from Guerriero 1995)

Although the change of thickness during movement is not documented, experience shows that shear zones at the base of mudslides are thicker (reaching a meter or more) than those bounding slides (Guerriero 1995; Comegna et al. 2004b). Theoretical considerations by Urciuoli (2002) and Picarelli et al. (2004) suggest that the shear zone progressively thickens ever since the beginning of its formation (i.e., before general slope failure). Probably, in mudslides, thickening continues after slope failure as a consequence of movement and incorporation of the topsoil of the underlain formation into the shear zone (Corominas 1995).

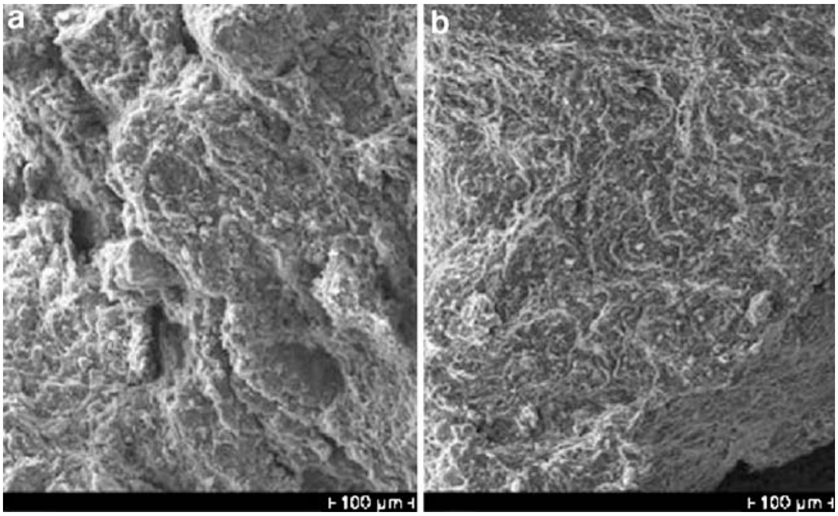
As shown by Hutchinson (1988), Vallejo (1989), and Picarelli (1993), the mudslide body above the shear zone is a complex material formed by lithorelicts (lumps) of the parent formation (generally, a stiff fissured clay or a clay shale) mixed with a softened clay matrix generated by degradation of lumps. However, Picarelli et al. (1998) and Comegna et al. (2004b) show that the shear zone materials can be quite uniform, including only small isolate lithorelicts spread within the clay matrix. This suggests that continuous stress changes, softening, and remoulding induced by the large strains experienced during movement cause a progressive breakage of the lithorelicts (Fig. 1). Clear evidences of segregation are not available. Finally, visual observation of the shear zone generally does not show any discontinuity apart from the slip surface. This indicates that the network of natural fissures featuring the parent formation and the shear discontinuities (minor shears) induced by slope failure (Skempton 1966) are cancelled by movements.

Referring to the particle arrangement, strong differences exist between investigated shear zones in silica sand, which have a dense core, and shear zones located at the base of mudslides. In fact, the water content, and thus, the void ratio, of the material in shear zones of mudslides is higher than that of the overlying landslide body and of the parent formation below. In particular, closely around the slip surface, the water content presents a sharp peak (Fig. 2). This "core" could represent a zone of well-aligned soil particles. Such a high water content could be due both to dilation induced by shearing and to swelling caused by local aperture of the walls of the slip surface and of the minor shears around it (Pellegrino et al. 2004). However, Lefebvre (1981) showed that the water content in the vicinity of the slip surface in a slightly overconsolidated sensitive clay can be lower than around it. These contrasting data can be partially justified by the different response of slightly and highly overconsolidated clays, which contract and dilate, respectively, when sheared. In sand, the formation of a dense core can depend on both fairly a low initial density and grain crushing, as suggested by the authors; in contrast, in mudslides, it is unlikely that disruption of the lithorelicts implies breakage of single clay particles and even of smaller clay plate aggregates.

The higher water content of the shear zone is indirectly revealed by microscopic investigations carried out with the scanning electron microscope (SEM). The material in the shear zone (Fig. 3b) is more uniform than in the mudslide body (Fig. 3a) and is formed by well-recognizable clay plate aggregates which are assembled so as to determine a more open fabric. In contrast, the mudslide material appears as an aggregate of silt-size lumps where clay plate aggregates are not visible at low magnification. This entails that porosity within and between aggregates in the shear zone is higher than in the mudslide body.

At higher magnification (Fig. 4) micropores between aggregates within the shear zone are widespread and more evident, as well as clay plates.

Fig. 3 SEM photographs at low magnification of the mudslide body (**a**) and of the shear zone (**b**)



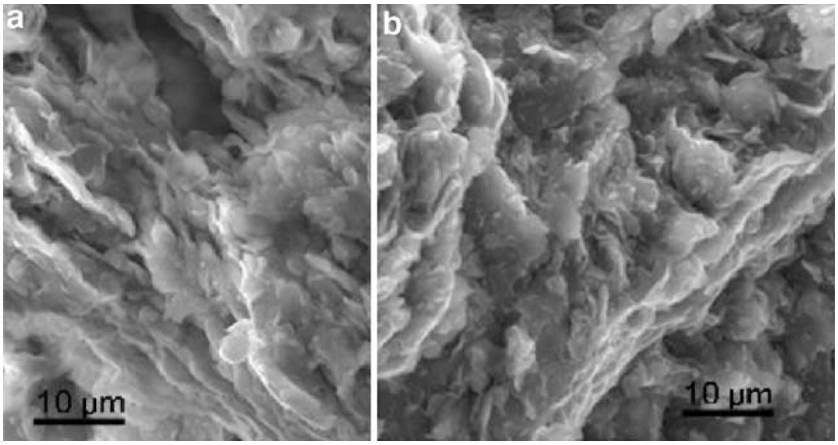


Fig. 4 SEM photographs at hgher magnification of the mudslide body (**a**) and of the shear zone (**b**)

As silica sand in the final steady-state condition, clay in the shear zone has quite an oriented fabric. Specimens observed at the SEM present small shear fissures which have the appearance of groups of shear structures with similar orientation separated by a clay matrix formed by aggregates that are aligned accordingly to the orientation of the more persistent structures (Fig. 5).

Unfortunately, literature on this subject is quite scarce, especially in the case of thick shear zones in mudslides. In fact, the major part of available data refers to shear fabric induced in the laboratory and to very thin shear discontinuities in stiff over-consolidated clay.

This locally observed fabric could be quite diffuse in the shear zone of mudslides, as demonstrated by laboratory tests. In fact, triaxial and direct shear tests indicate that in the direction of mudslide movement, the shear strength coincides with the critical one, while in the direction normal to it, this is slightly larger. Naturally, along the slip surface, the operative shear strength is at residual. Also, permeability tests show a clear anisotropy in the coefficient of conductivity (Comegna 2004; Comegna et al. 2004b).

Authors' response

The authors wish to thank the discussers for their consideration of the authors' paper and for providing parallel research results obtained from the shear zone in clay. We are pleased to see that some similar research results had been obtained from researches performed by the authors and discussers. Generally speaking, we support the discussers' comments and believe that the research results presented by the discussers will be of great interest to landslide researchers.

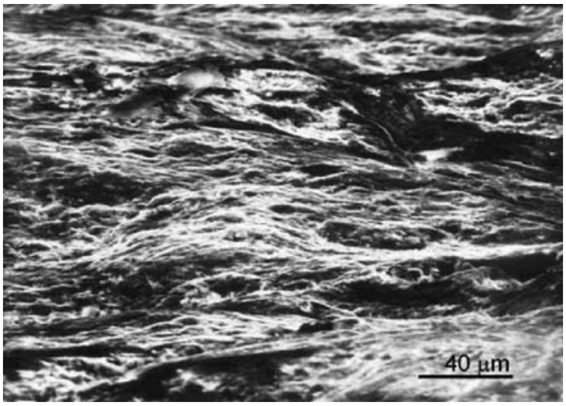


Fig. 5 SEM photograph at medium magnification of a specimen taken from the shear zone showing a few millimeters-long shear discontinuities

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