LARGE-SCALE MUDSLIDES IN STRUCTURALLY COMPLEX CLAY SHALES IN THE NORTHERN APENNINES (ITALY)

GLISSEMENTS DE BOUE A GRANDE ECHELLE DANS DES ARGILITES STRUCTURELEMENT COMPLEXES DE L'APENNIN SEPTENTRIONAL (ITALIE)

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SYNOPSIS: Many slope instability phenomena affect outcrops of structurally complex clay shales, known as "Argille Scagliose" or "Chaotic Complex", in the Northern Apennines. This paper examines five large-scale flow-like mass movements on argillaceous slopes, around a rock slab, near Chiusi della Verna (Tuscany, Italy). They can mainly be classified as mudslides on the basis of the morphological characteristics and of the involved material . The geotechnical and geological problems connected with the interpretation of the mechanisms of movement are analysed and discussed.
Two main problems arise from the study of these mass movements. Firstly there is an inconsistency between the large volume of the tracks and the accumulation zones and the small extension of the source areas, since a morphometric analysis showed that the latter are about 10% of the former. Secondly, the mudslides are scarcely active in the present day conditions and the results of the back-analysis show that their movement would require high values of pore water pressures for a large part of the tracks, a condition that does not seem reasonable in the present day climate. Two main factors can be considered to explain these facts. The effect of thawing of ground ice, under periglacial climatic conditions in the Upper Pleistocene and the extrusion and squeezing-out of large volumes of material due to the release of high in situ horizontal stress induced by the recent tectonic activity. Reactivations od the mudslides in the upper sector can be caused by critical water table conditions, due to water flowing out from the overlying rock slab, and by undrained loading due to falls from the rock cliffs.

INTRODUCTION

Many slope instability phenomena in the Northern Apennines affect outcrops of highly tectonized clay shales; they consist mainly of landslides and flow-like mass movements. The instability is determined by the bad geotechnical properties of the terrains, by the chaoticization induced by the tectonic activity, by the marked deepening of the drainage network and by the climatic fluctuations during the Pleistocene. All these factors caused the occurrence of large scale mass movements, the detection and analysis of which led to some geotechnical problems. Their recognition and study is the object of a research program in the context of the research line on the "Forecast and Prevention of High Risk Mass Movements" of the Italian National Research Council.
This paper deals with some large-scale flow-like slope movements developed around a rock butte, in a zone of the Tuscan Apennines (Italy). After a brief geological outline, the results of a morphometric analysis are given and some data concerning the geotechnical properties of the materials are presented, together with a discussion on the difficulties of their characterisation. Then a simple back-analysis of the movements is proposed. Finally the problems of the interpretations of the mechanism and of the causes of their movement are analysed and discussed.

GEOLOGICAL OUTLINES AND MORPHOMETRIC ANALYSIS

The studied area is located in Tuscany, in the basin of the Arno River, in a mountain region of the Apennine chain, near the town of Chiusi della Verna. The majority of the slope instability phenomena are associated with outcrops of argillaceous terrains, known by the informal names of "Argille Scagliose" (Scaly Clays) or "Chaotic Complex". These terrains constitute the basal complexes of allochthonous sheets, known as Ligurian Units, which underwent wide horizontal tectonic movements during the Apennine orogenesis. These huge horizontal movements caused the complete disarrangement and deformation of the terrains, with the chaotic mixing of tectonically deformed clay shales and terrains with a brecciated structure, formed by submarine gravitational flows during the orogenesis. From a lithological point of view these terrains are made up of varicoloured fissured mudstones and clay shales, embedding blocks and strata of rock.
Calcarenites and sandtones, belonging to the semi-allochthonous Epiligurian Units, constitute isolated slabs or buttes over the argillaceous slopes. Five large-scale flow-like mass movements have been detected around a calcarenitic rock butte near Chiusi della Verna (Fig.1).
The materials involved in the movements are mainly clays and clay shales with debris and rock blocks fallen from the slab. Rock blocks tilted in different ways are scattered on the surface and they can also be found at considerable distances (some kilometres) away from the rock cliffs. Frequently these blocks reach exceptional dimensions (tens of cubic metres). The movements affect essentially argillaceous materials, whereas debris and rock blocks are passively transported. The presence of lateral shear zones, polished and slickensided, suggests that the main mechanism of movement is sliding rather than flow, with subordinate internal viscous deformations, at least in their proximal sector. This feature allows us to classify these mass movements as "mudslides" (Hutchinson & Bhandari, 1971).
All five large mudslides are inactive at present, with the exception of smaller superficial reactivations, in the upper sector, and no measure of displacement or velocity is available. However the morphological characteristics suggest that the pattern of movement can be considered similar to the "complex sliding block" or the "complex slide-plug" described in Brunsden (1984).
A geomorphological survey, carried out using air photographs (scale 1 : 13 500) and detailed topographic maps (scale 1 : 5 000 and 1 : 10 000), allows us to obtain some morphometric parameters of the five mudslides (Tab.1). The estimation of the depths has been based on geomorphological considerations, reconstructing the pre-existing topography of the valleys on the basis of morphometric data in adjacent zones and extrapolating the slope of the valley flanks (Fig.2). On the basis of their ratio width/length these phenomena can be classified as "elongate" mudslides (Hutchinson, 1988).
The source zones of the five mudslides are quite limited in extent, since the tracks start just near the foot of the rock slab. Parts of the source areas are covered by debris fallen from the rock cliff. The track is the most developed sector of these mudslides. The course and the form of the tracks are dictated by the surface relief, since they tend to follow the course of V-shaped fluvial valleys, producing a typical convexity in their bottom. Brooks and erosional gullies are present on both sides of the track. Lateral ridges with evident slikensides and shear zones are developed at their boundaries.

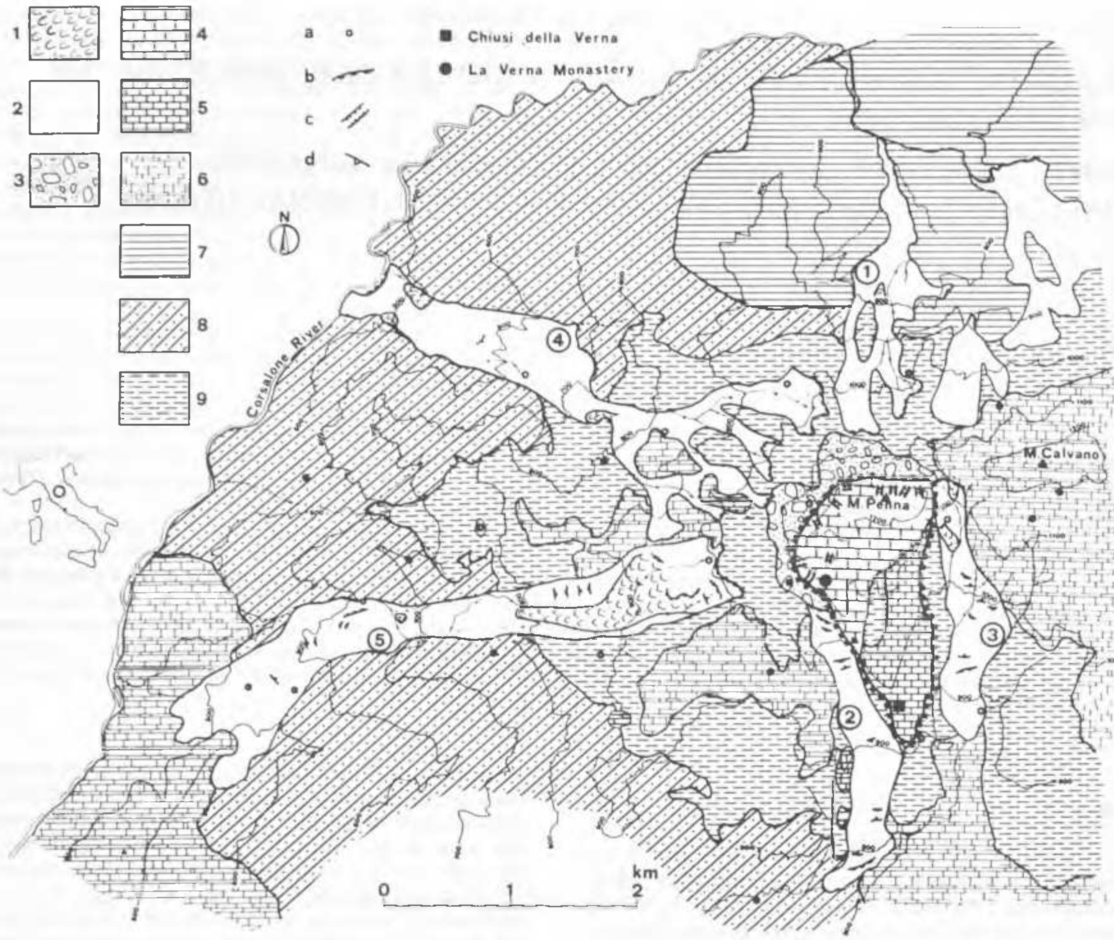

Fig.1 - Geological and geomorphological map: 1) active mudslide; 2) inactive mudslide; 3) coarse debris; 4) calcarenites; 5) sandstones; 6) alternance of limestones, sandstones and marlstones, 7) marlstones; 8) sandstones; 9) clay shales. a) spring or swamp; b) scarp; c) trench; d) counterslope. Circled numbers refers to the location of the five main inactive mudslides.

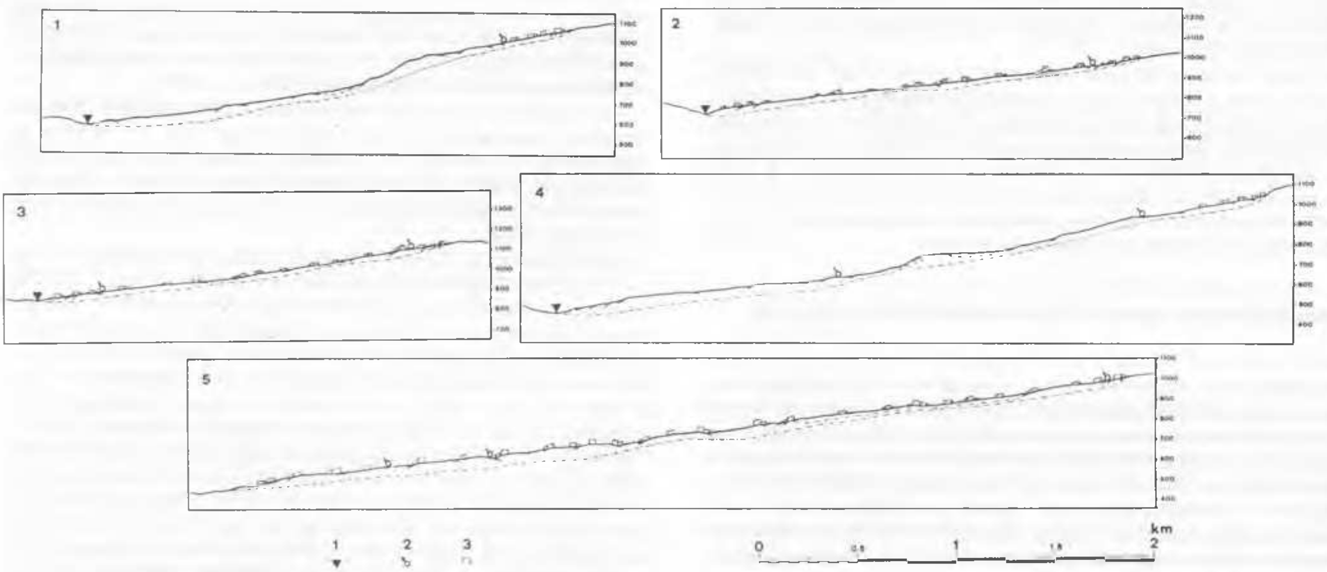

Fig.2 - Schematic longitudinal sections. 1) stream in erosion; 2) spring or swamp; 3) blocks of calcarenites.

Table 1 - Main morphometric parameters of the mudslides.

N	max length (m)	max width (m)	min width (m)	difference in altitude (m)	mean gradient (°)	max depth (m)	volume ($10^6 m^3$)
1	2350	600	50	495	9	40	14.4
2	2300	400	190	290	7	25	8.1
3	2080	450	220	265	7.5	25	11.6
4	1900	630	130	280	8	70	21.3
5	4750	750	250	559	6.5	80	71.8
					Total volume:		**127.2 x10^6 m^3**

The accumulation zones tend to take the form of expanded lobes and their perimeter is always bordered by a stream and is affected by intense erosive phenomena. For this reason the accumulation zones are not well-developed and represent the remains of larger lobes dismantled by the erosion.
The total volume of material involved in the tracks and in the accumulation zones of the five major mudslides can be estimated to about 10^8 m^3. The volume of the source areas is difficult to estimate because of the erosion and the debris cover; a gross estimation suggests that it is in the region of 10% of the volume of the tracks and accumulation zones. Hence the first question that arises from this morphometric analysis is the inconsistency between the large volume of the tracks and the accumulation zones and the small extension of the source areas. A geotechnical characterisation of the materials is necessary in order to assess the influence of swelling phenomena.

GEOTECHNICAL PROPERTIES

The terrains belonging to the basal complexes of the Ligurian Units in the Apennines exhibit a classic "complex geotechnical behaviour" (Esu, 1979), as they are characterised by lithological and structural complexity. The lithological complexity is connected to the heterogeneity of the materials, in particular to the presence of more constituents, with marked contrast in their geotechnical properties, as rock blocks and strata embedded in a clay shale matrix. Moreover, the mineralogy and the granulometry of the matrix is quite variable, probably as a consequence of the tectonic stresses which caused the chaotic mixing of different types of clays.
The main index properties for the classification of the materials are listed in Tab.2. The materials are mainly clayey silts of intermediate plasticity. The values of the "activity index" and of the "free swelling index" are quite low, and show a medium-low tendency to swelling. The calcium carbonate content is quite variable and controls the degree of cementation.
The structural complexity is an effect of the tectonic history: the terrains are made up of an assemblage of iso-oriented flat scales, with dimension of the order of millimetres or centimetres. The surface of the scales is polished and slickensided as a consequence of tectonic shears. Evidences of shear are also manifest on the surface of the rock blocks embedded in the clayey matrix. The high degree of tectonization brought about a chaotic arrangement of the shear zones, rather than the presence of individual shear surfaces.
The scaly structure leads to a strong scale dependency of the mechanical properties but the assessment of a representative elemental volume is quite difficult. The mechanical behaviour of the materials is also complicated by the lithification, due to different degrees of cementation of the fissures caused by the ground water. Both the fissuring and the cementation lead to a strong sensitivity of the mechanical properties to remoulding, so that for the complete characterisation, it is advisable to perform tests both on intact undisturbed samples and on reconstituted specimens.

Table 2 - Main index properties of the clay shales. CF: clay fraction; LL: liquid limit; PI: plasticity index; wo: natural water content; Ac: activity index; FSI: free swelling index; γ: unit weigth; $CaCO_3$: carbonatic fraction; ECM: expandable clay minerals (% relative to the clay fraction).

CF (%)	LL (%)	PI (%)	wo (%)	Ac (-)	FSI (%)	γ (kN/m^3)	$CaCO_3$ (%)	ECM (%)
36-55	33-46	14-23	9-17	.3-.6	29-54	19-20	6-35	33-46

Oedometric tests were performed on a sample taken at shallow depth near the source of one of the major mudslides (Fig.3); the compression and the swelling indices of the undisturbed material result very low, as a consequence of the iso-oriented structure; in contrast the "intrinsic" compression and swelling indices (Burland, 1990), determined on reconstituted material, are considerably higher. This suggests that an increase in void ratio, even of 30%, in excess of that determined by simple swelling could be caused by the loss of structure.
The shear strength of the materials has been estimated carrying out direct shear box tests (Fig.4). The peak strength data, determined on undisturbed samples, are quite scattered, as a consequence of the variable degree of fissuring and cementation. The mean envelope is curved with quite high strength parameters, probably as a consequence of the incipient lithification and by the scaly structure. The high strength and low brittleness at low stress levels of the scaly material could be interpreted as a result of a "granular-type" behaviour. Tests on reconstituted normally consolidated samples, for the determination of the "critical state strength", give a linear envelope with a friction angle of 25-26°. The residual strength envelope, determined with reversal shear box tests, is curvilinear at low stress levels and, in the stress range 0.1-0.4 MPa, is characterised by ϕ'_r = 14-15°. A lower value of 12° is obtained for ring shear test, but this figure seems to be slightly underestimated taking into account the relatively low clay fraction.

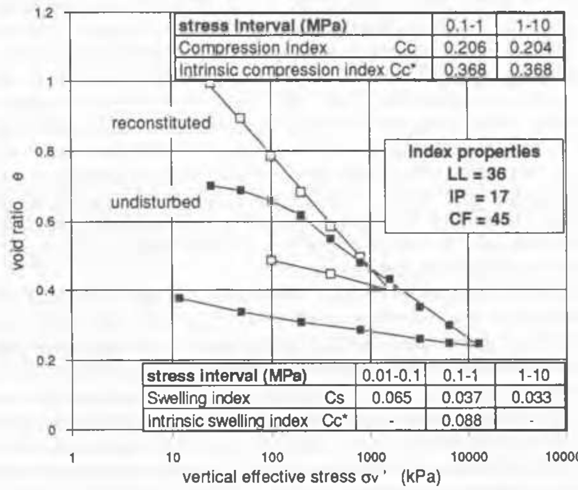

Fig.3 - Results of oedometric tests on undisturbed and reconstituted samples.

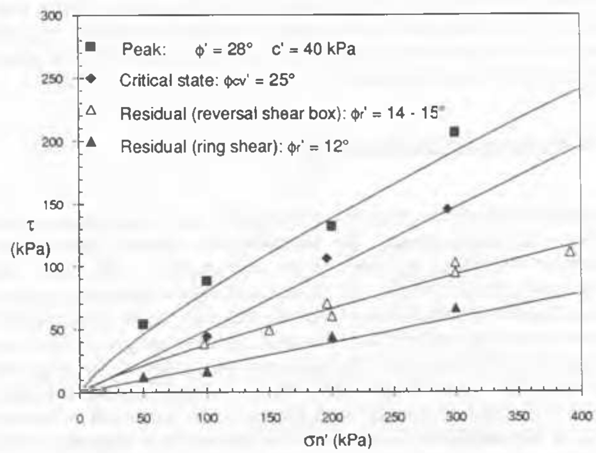

Fig.4 - Results of shear strength tests on undisturbed and reconstituted samples.

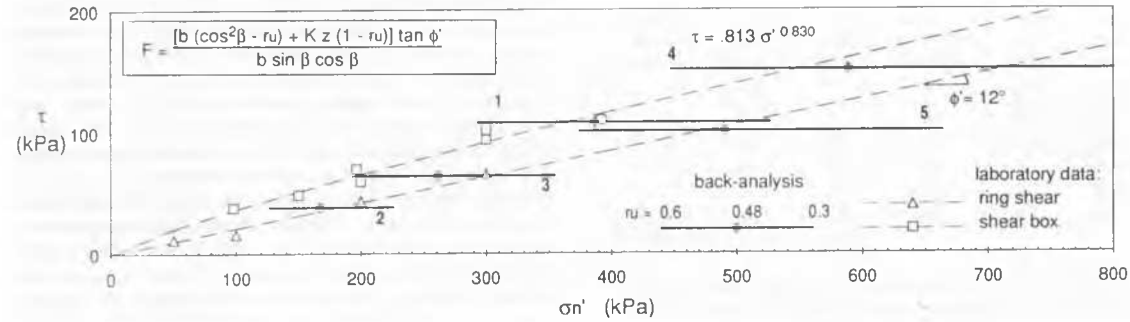

Fig.5 - Results of the back-analysis for different values of the pore water pressure ratio r_u. Numbers refers to the five major mudslides shown Fig.1.

BACK-ANALYSIS

A simple "infinite slope analysis" on the mudslide tracks was carried out for the back-analysis, since the depth/length ratio is sufficiently low. This analysis is based on the assumption that the movements occur essentially by basal translational shear. However the high depth/width ratio suggests that the occurrence of lateral shears can have an important influence. Therefore we chose to utilise the equation proposed by Chandler (1972) for the analysis of rectangular channels limited by lateral shears, shown in Fig.5. The lateral stress coefficient K was taken equal to 0.56. For each mudslide the normal stress acting on the basal and lateral shear surfaces and the shear stress required for the movement are computed for different values of the pore pressure ratio r_u; the results are compared with the laboratory residual strength data (Fig.5). For the water table at ground level, assuming seepage parallel to the slope ($r_u = 0.48$) the values of the back-analysed friction angle range between 11.7° and 15.6°, and they are consistent with the range of laboratory values of residual friction.

These simple calculations allow us to conclude that the main mechanism governing the large mudslides is likely to be a basal and lateral shear controlled by the residual strength. The position of the water table has a critical role in determining stability conditions or reactivations. If we consider the residual shear strength determined with the reversal direct shear test as the most representative, then the movement requires conditions of the water table at ground level, or slightly artesian. The reactivation of the mudslides in their proximal part, near the rock slab, during the wet seasons, could be explained by the onset of critical conditions of pore water pressure, for the water table at ground level, as is demonstrated by the presence of springs and small swamps at the border of the slabs. Transient high values of pore water pressure can also be caused by undrained loading of the mudslides due to the continuous yield of debris fallen from the rock slab (Hutchinson & Bhandari, 1971). However the motion of the whole mudslides would require the maintaining of high values of pore water pressure, for a large part of the tracks, a condition that does not seem reasonable in the present day conditions, as it is highlighted by the present inactivity of the larger phenomena.

DISCUSSION AND CONCLUSIONS

The interpretation of the origin of the large scale-mass movements examined involves several problems. The morphometric analysis highlight the volumetric deficit of the source areas with respect to the tracks and accumulation zones. This fact can be explained only in a minimum part by the contribution of material fallen from the rock slab. As far as the swelling phenomena in clay minerals are concerned, the index properties show that the materials are characterised by a relatively low tendency to swelling, from a mineralogical point of view. The increase in volume seems essentially related to the loss of structure probably due to the unloading of fissured materials in presence of water or ice. This phenomenon, analogous to the softening process, leads to the production of clayey debris and softened clays, with a higher void ratio than that determined by simple swelling.

However even this phenomenon does not seem sufficient to explain the large deficit of volume of the source areas. So this requires a different interpretation, within the context of the overall mechanism of instability in the area, which also affect the overlying rock slab. In fact the extrusion of large volumes of material could probably be linked to slow squeezing-out phenomena, due to the release of high values of horizontal tectonic stress, triggered off by the valley erosion. It is known that in zones of recent orogenesis, tectonic activity can cause high in situ horizontal stress values which can be close to the passive Rankine's state of the material. The valleyward extrusion of softened clayey material could also be enhanced by periglacial processes and by the pre-existing shears induced tectonics.

The role of periglacial processes, with the consequent generation of artesian pore water pressures, proves to be important also from the analysis of the mechanisms of the movements. The back analysis shows that the sliding is controlled by the residual strength parameters of the clay shales, for high values of the pore water pressure ratio, corresponding to water table at ground level, or slightly artesian conditions. These conditions are reached in the wet season for the upper part of the mudslides and determine their reactivation. However, the motion of the whole major mudslides does not seem possible in present day conditions and it is probably occurred under periglacial climatic conditions in the Pleistocene. The thawing of ground ice leads to a decay of shear strength and the onset of artesian pore water pressure by undrained self-loading (Hutchinson, 1988); the combination of these two effects could bring about the movement of large masses of material. Very little is known about the climatic conditions in the Apennines during the Pleistocene, and investigations are still at the beginning.

All these considerations have enhanced the difficulties of the analysis of the large-scale phenomena. In fact it can be carried out with the conventional methods only in part, as many factors, which traditional analyses do not take into account, as for example, tectonic and paleo-climatic effects, can play fundamental roles. Further work is necessary to fully clarify the mechanisms of movements and in particular the relationship between the mudslides and other types of instability phenomena in the area. This task is the object of a research program still in progress.

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