RESEARCH ON COMPLEX GRAVITATIONAL SLOPE MOVEMENTS IN THE NORTHERN APENNINES (ITALY)

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Abstract

Some cases of complex gravitational slope deformations occurring along the Po Valley side of the Northern Apennines are considered. In the past many situations now definitely ascribed to gravitational movements had been wrongly interpreted as the result of tectonic activity or karst processes. The present tendency to consider slope movements affecting complex situations, due to fractured calcareous or arenaceous rocks directly overlying clayey weak rocks, as deep-seated gravitational slope deformations is discussed. The results of the research show that in many cases it is not possible to apply to these movements simple mechanisms of failure, owing to the complexity of the structural situations and the variability of the substratum's geotechnical and geomechanical characteristics. The importance of a correct interpretation of the geomorphological features is also emphasized, since similar landforms could derive from totally different processes.

Key words: Complex landslides, Deep-Seated Gravitational Slope Deformations, Northern Apennines.

Riassunto

Ricerche sui movimenti di versante complessi nell'Appennino Settentrionale. Vengono considerati alcuni casi di movimenti franosi complessi sviluppatisi lungo il versante padano dell'Appennino Settentrionale. In passato molte situazioni attualmente riconosciute come determinate da movimenti gravitativi erano state erroneamente interpretate come il risultato di attività tettoniche o di processi carsici. L'attuale tendenza di considerare movimenti franosi associati a situazioni geologiche complesse, dovute alla sovrapposizione di rocce competenti fratturate su substrati argillosi, come deformazioni gravitative profonde di versante è discussa alla luce dei dati acquisiti nelle aree di indagine. La complessità delle condizioni strutturali e la grande variabilità delle caratteristiche geotecniche e geomeccaniche dei terreni d'appoggio non consentono di applicare sempre a questo tipo di frane semplici modelli di rottura. Viene infine evidenziata l'importanza di una corretta interpretazione degli elementi morfologici, poiché forme simili possono derivare da processi molto diversi.

Termini chiave: Frane complesse, Deformazioni Gravitative Profonde di Versante, Appennino Settentrionale.

1. INTRODUCTION

The investigations aimed at a better understanding and definition of complex landslides affecting sequences of rocks characterised by strong contrast of competence have received new interest and momentum during the past twenty years. In particular, the situations due to the superimposition of competent rocks on clayey ductile substrata are very frequent and give rise to complex gravitational movements about which it has long been difficult to recognise the real mechanisms responsible for these deformations.

After the impulse given to these

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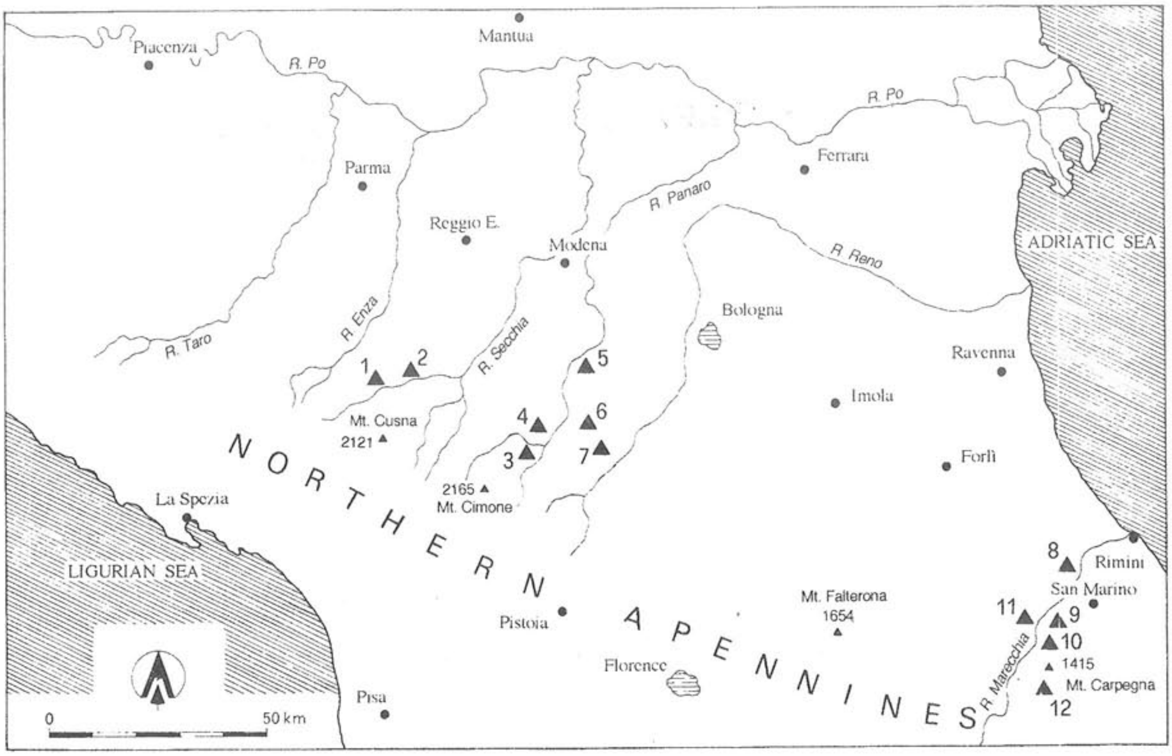

Fig. 1 - Location of complex gravitational slope movements in the Northern Apennines investigated by the Modena University Research Group in Engineering Geology: 1) Pietra di Bismantova; 2) Monte Valestra; 3) Acquaria; 4) Gaiato; 5) Guiglia; 6) Zocca and Montese; 7) Castel d'Aiano; 8) Torriana, Montebello and Verucchio; 9) San Leo; 10) Pennabilli; 11) Rocca Pratiffi; 12) Sasso di Simone and Simoncello.

investigations by several authors describing deep-seated slope deformations developed along the main mountain ranges of Europe (*Jahn,* 1964; *Kamenov et al.,* 1977; *Nemcok,* 1972; *Pasek,* 1974; *Ter-Stepanian,* 1977 and 1992; *Zaruba & Mencl,* 1982) and the first descriptions of similar complex mass movements in Italy (*Agnesi et al.,* 1984; *Dramis et al.,* 1985; *Engelen,* 1963; *Forcella,* 1984; *Guerricchio & Melidoro,* 1973 and 1979; *Sorriso-Valvo,* 1984, 1988 and 1989; *Sorriso-Valvo & Crescenti,* 1987), the Research Group in Engineering Geology of Modena University has directed most of its interests to the study of landslips in the Northern Apennines that from an immediate morphological approach could be ascribed to deep-seated gravitational slope deformations (Fig. 1). Previously the geometrical characteristics of the rock masses involved in these movements had been interpreted as the product of tectonic displacements (faults) while some typical landforms actually due to gravitational deformations (such as trenches, long opened cracks, gulls, closed depressions etc.) had been attributed to karst-type phenomena. In order to better explain the mechanisms generating this kind of features, the research has been articulated in a programme of investigations concerning the following aspects:

a) geological survey and analysis of structural and morphological factors connected with deep-seated slope deformations;

b) identification of failure features typical of competent materials overlying weak rocks showing plastic-viscous behaviour;

c) relationships between structural elements and distribution of fracture systems;

d) mineralogical and geotechnical characterisation of the substratum and type and evolution of slope movements.

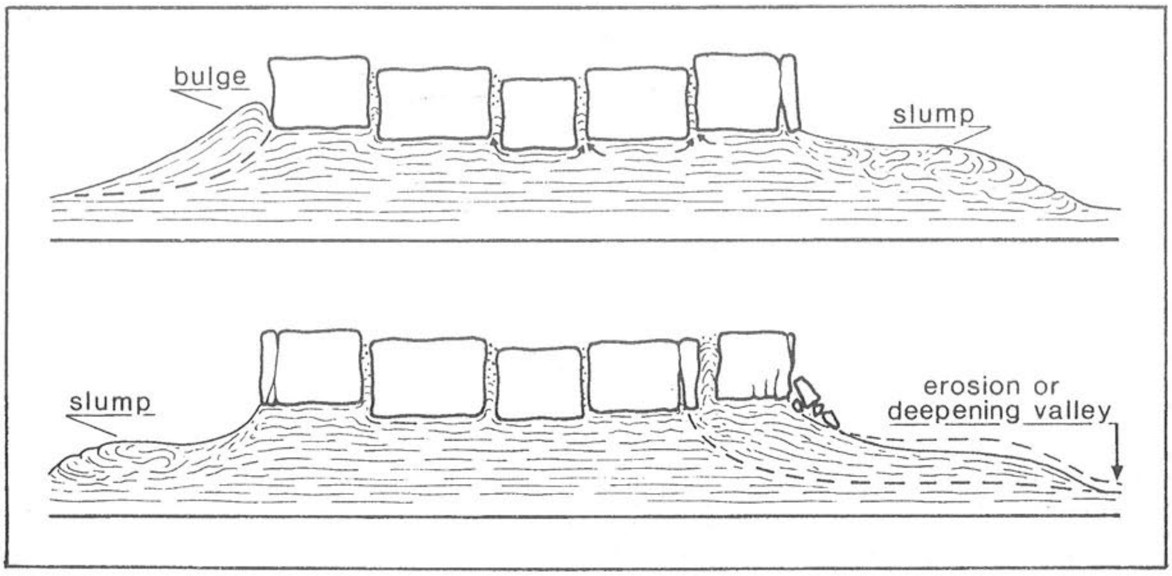

Fig. 2 - Intermediate stages of failure of a competent plate overlying a ductile homogeneous substratum (after *Cancelli & Pellegrini*, 1987).

In particular, after the definition of a model of failure developed at the onset of these investigations by *Cancelli & Pellegrini* (1987), several situations were taken into account (Fig. 1) in the provinces of Modena (Acquaria, Gaiato, Guiglia, Zocca and Montese), Bologna (Castel d'Aiano), Reggio Emilia (Pietra di Bismantova and Monte Valestra), Forlì (Torriana, Montebello and Verucchio), San Marino, Pesaro-Urbino (San Leo, Pennabilli, Rocca Pratiffi), Arezzo and Pesaro-Urbino (Sasso di Simone and Simoncello). The mechanism of failure proposed (Fig. 2) compares a competent plate lying on a clayey substratum to an elastic superficial raft foundation resting on a compressible medium. In the real situations, the lithic plates are always affected by dense fracture networks that control the independent movements of the rock blocks since more pronounced differential settlements would take place in the central part of the substratum, with a squeezing out effect of the soft rocks towards the less confined outer margins and formation of bulges that would eventually give rise to slumps (*Cancelli et al.*, 1987; *Colombetti & Tosatti*, 1987).

The considerations expressed hereafter discuss the limits of applicability of the previously illustrated model to some of the cases examined.

2. THE ACQUARIA LANDSLIDES (PROVINCE OF MODENA)

The village of Acquaria is located on top of a large calcareous-marly cliff (1045 m) belonging to the Monte Venere Flysch (Upper Cretaceous-Paleocene) overlying the fissured clayshales of the Argille a Palombini Formation (Lower Cretaceous-Cenomanian) in the catchment basin of the River Panaro (Province of Modena, northern Italy). The contrast of competence between the two formations involved in slope movements is very high, thus propagating in time marked conditions of instability along the margins of the slabs.

The most evident morphological features are given by a double trench at the top of the cliff separated by a small elongated ridge (Fig. 3). The run-off ditches and streams collect their water into closed depressions that owing to the lithological characteristics of the turbiditic formation (alternation of

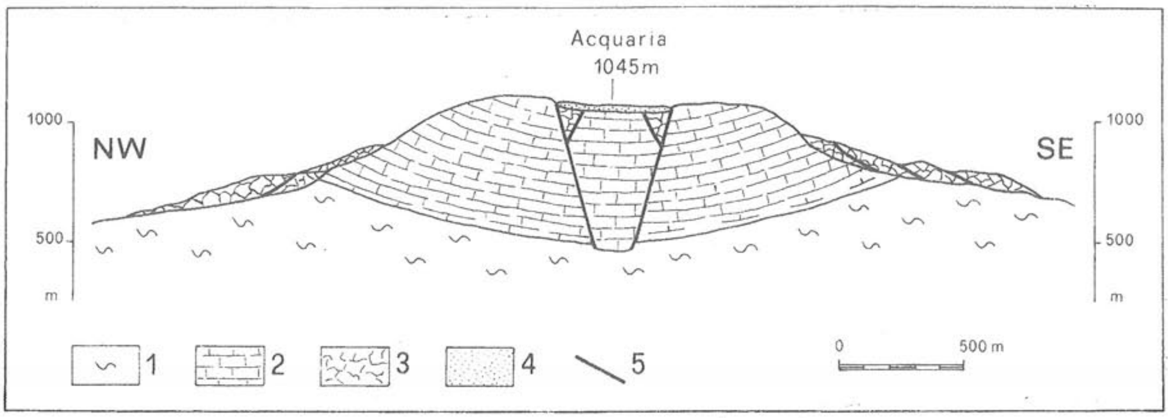

Fig. 3 - Geological section of the Acquaria slab. Legend: 1) Argille a Palombini Formation (Lower Cretaceous-Cenomanian): high-plasticity fissured clays and clayshales with lithic inclusions; 2) Monte Venere Flysch (Upper Cretaceous-Paleocene): calcareous-marly turbidites with clayey and arenaceous intercalations; 3) dismembered and collapsed blocks of Monte Venere Flysch feeding the marginal landslides; 4) eluvial and colluvial deposits; 5) main rupture surfaces (after *Cancelli et al.*, 1987).

marly and calcareous levels), could not be ascribed to karst processes.

The relief morphological evolution seems to be controlled by a deep-seated gravitational deformation along two main rupture surfaces that affect the whole thickness of the slab (Fig. 3), similarly to a model proposed by *Beck* (1968) for analogous situations described in the Southern Alps of New Zealand. The sagging of the cliff's central block is caused by more pronounced settlements in the underlying ductile clayshales which, through a squeezing out displacement, slowly move towards the less confined outer margins.

The slope deformation is therefore interpreted as a general lateral spreading of the rock blocks accompanied along the edges by rock and debris slumps. At the boundary with the clayey substratum these landslips evolve into vast earth flows that are periodically reactivated. In 1939 part of the village of Acquaria was destroyed by one of these removements (*Cancelli et al.*, 1987; *Tosatti*, 1987).

3. PIETRA DI BISMANTOVA (PROVINCE OF REGGIO EMILIA)

Pietra di Bismantova, rising in the Reggio Emilia district (northern Italy) at a maximum altitude of 1046 m, represents an outstanding feature in the whole area, owing to its square shape and vertical slopes, in marked contrast with the surrounding landscape (Fig. 4). It gives the name to an important clastic sequence of the Emilia Apennines: the Bismantova Formation (Lower-Middle Miocene).

According to its morphological and structural characteristics, the Pietra di Bismantova plate can be subdivided into two portions: a rectangular tabular-shaped sector and an arcuated smaller part. This massif slab is made up of arenaceous limestones rich in bioclasts of the Bismantova Formation (Middle Miocene) lying partially on the cherty marlstones of the Antognola Formation (Lower Miocene) and on the fissured polychromic clays and clayshales of the Argille Varicolori Formation (Upper Cretaceous-Lower Eocene).

The most evident characteristic of Pietra di Bismanova is given by the numerous fractures that subdivide it into several blocks. The origin of these widespread fracture systems seems to derive from the intense tectonic stresses that have accompanied the transfer and emplacement

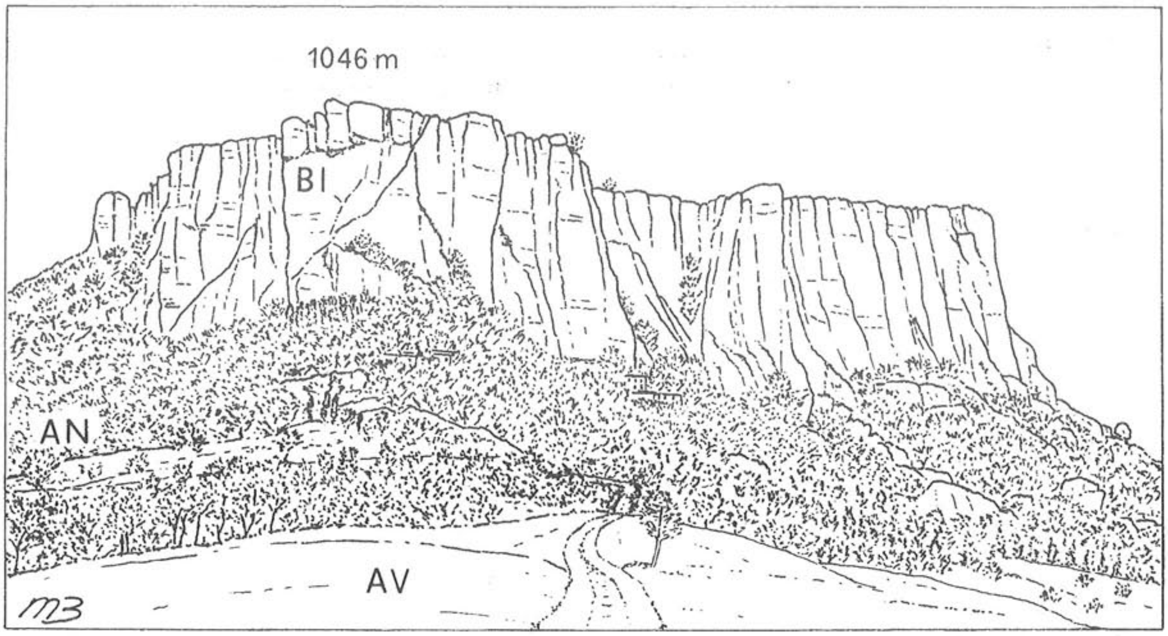

Fig. 4 - South view of Pietra di Bismantova showing main fractures and wedge-shaped lowered central portion. AV = Argille Varicolori Formation (Upper Cretaceous-Lower Eocene): overconsolidated fissured clays and clayshales; AN = Antognola Formation (Lower Miocene): cherty pelites and marlstones; BI = Bismantova Formation (Middle Miocene): bioclastic arenaceous limestones.

of the Ligurian sequences and of the overlying Epiligurian formations.

In the central portion, wedge-shaped blocks are noticeable; they appear to be lowered compared with the adjacent areas along systems of antithetical fractures and are particularly well exposed along the southern slope (Fig. 4).

The general situation of Pietra di Bismantova is characterised by widespread instability both in the competent rocks and the underlying substratum. The rock blocks tend towards a progressive opening of the fractures, which along the outer margins give origin to rock falls and topples, while in the substratum several earth slides evolving into flows are present, especially where the more deformable clays of the Argille Varicolori Formation directly outcrop, that is along the eastern side of the cliff.

When the model of failure previously illustrated was first applied to complex landslides affecting superimpositions of competent rocks on incompetent ones, it seemed that Pietra di Bismantova fitted perfectly into this scheme of deep-seated gravitational deformation (*Cancelli et al.*, 1987). More detailed geological investigations have instead shown for this limestone cliff a structurally complex situation, deriving mostly from the different nature and mechanical characteristics of the substratum soils (*Conti & Tosatti,* 1993c).

The marked depressions related to the lowered central blocks cannot be ascribed to plastic-viscous settlements of the substratum, which in this sector is made up of a thick competent sequence of cherty pelites and indurated marlstones, but rather to a system of normal and transcurrent faults that cut through the slab and affect also the underlying rocks. One of these faults marks the tectonic boundary between the Epiligurian sequence of the Ranzano and Antognola Formations and the polychromic clays belonging to the Ligurian units. The Pietra di Bismantova slab was emplaced on top of these formations and was partially affected by removements along these important structural discontinuities.

The present situation of instability of the large portion of the rock plate cannot therefore be related to gravitation-induced settlements in a homogeneous ductile substratum, but rather to a general extension effect due to a decrease of the confining pressure along the eastern margin, where the substratum is made up of directly outcropping argillaceous weak rocks, constantly mobilised by landslides. Thus the support for the overstanding rocks would be compromised, increasing the extension stresses along the pre-existing structural fractures, according to a model of failure developed by *Cloos* (1968) in his experiments on fracture patterns.

The morphological evidence on top of the rectangular portion of the slab confirms a general trend toward a further opening of the cracks, with formation of trenches and aligned depressions along the structural discontinuities.

Only in correspondence with the arcuated portion of the slab, which lies directly on the Argille Varicolori clayshales, is it possible to ascribe the accentuated dismembering and collapse of the rock blocks to a squeezing out effect of the substratum. Therefore, the arc-shaped north-eastern sector of Pietra di Bismantova derives its origin from the crowns and surfaces of rupture of the slump-earth flows particulary widespread along this margin. Their periodical removement is confirmed by the frequent tension cracks and displacements found on several buildings located at the toes of these landslides.

4. THE CLIFF OF SAN LEO (PROVINCE OF PESARO-URBINO)

The competent plate where the ancient village of San Leo lies (639 m), rises in the middle portion of the River Marecchia valley (Province of Pesaro-Urbino, central Italy) and is famous for its large castle and other important monuments of various epochs. This rocky cliff is made up, from the bottom to the top, of the San Marino Formation organogenous limestones (Lower-Middle Miocene) and the Monte Fumaiolo glauconitic sandstones (Middle Miocene) with cross-bedding and thin marly intercalations (Fig. 5). The San Marino Formation derives its name from the main outcrop of these fossiliferous limestones, that is the cliff on which the oldest part of the Republic of San Marino rises; it corresponds to the Bismantova Formation in the Emilia Apennines. The substratum is homogeneous in all its extension, being made up of high-plasticity clayshales belonging to the Argille Varicolori Formation (Cretaceous-Eocene).

From a structural viewpoint, this slab is characterised by an arcuate arrangement of the cliff, with convexity facing ENE and a fan-shaped system of sub-vertical fractures. Other important groupings of fractures subdivide the plate into several blocks, progressively lowered to the west. A third fracture system, with a sub-horizontal attitude, plays a major rôle in the movement of the blocks towards the outer margins (Fig. 5). All the fracture systems investigated clearly result from a compressive tectonic origin, following the overthrust movements which have accompanied the emplacement of the Marecchia valley allochthonous sheet (*Conti & Tosatti,* 1991 and 1993a).

Like many other villages of this region, also San Leo was built on top of a limestone cliff because of its privileged dominant position over the valley. Unfortunately the geological and mechanical characteristics of these competent slabs and their argillaceous substratum have always favoured the formation of several gravitational movements that directly threaten the conservation of many buildings.

In San Leo the landslides are particularly widespread and affect both the calcareous-

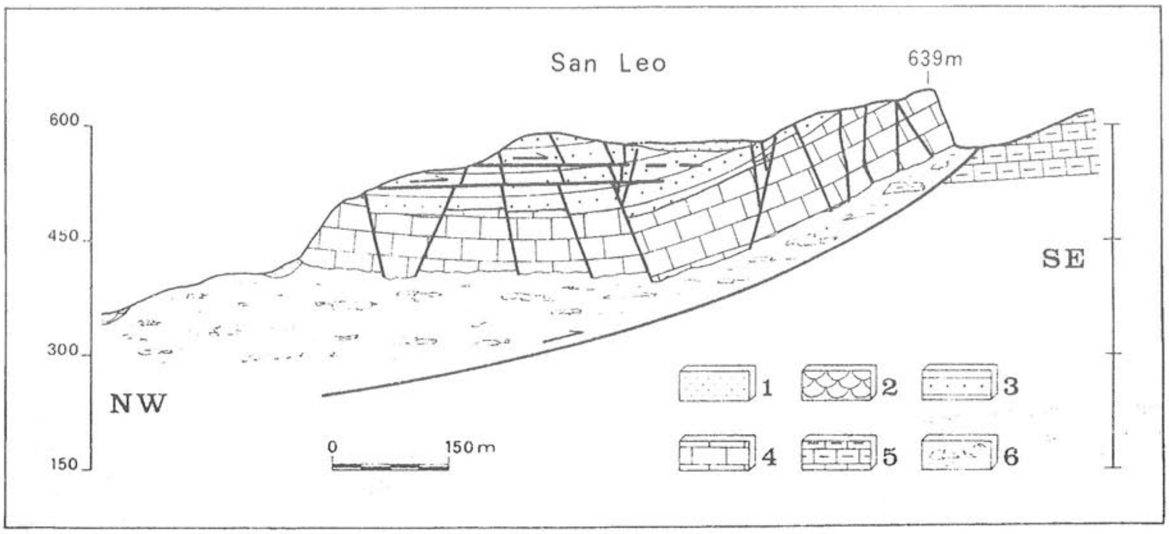

Fig. 5 - Geological section of San Leo. Legend: 1) eluvial and colluvial deposits; 2) active earth flows; 3) Monte Fumaiolo Formation (Middle Miocene): cross-bedding glauconitic sandstones with thin marly intercalations; 4) San Marino Formation (Lower-Middle Miocene): organogenous limestones; 5) Monte Morello Formation (Lower-Middle Eocene): turbiditic marly limestones, calcarenites and clayey marlstones; 6) Argille Varicolori Formation (Upper Cretaceous-Lower Eocene): high plasticity overconsolidated and fissured clays and clayshales (after *Conti & Tosatti*, 1991).

arenaceous rocks, with rock falls and topples, and the substratum weak rocks, with slumps and earth flows. The most intense movements are recorded along the outer margin of the arcuate structure, with occasional detachments of wedge-shaped boulders, even of considerable dimensions. Rotational slides in the less confined clays along the margins involve in their movement also the overlying competent formations, thus giving origin to complex landslides. The slope movements along the plate boundaries are nevertheless only favoured by the structural conditions, since their main cause seems to be induced by the long-term differential settlements of the clayey substratum, owing to the load stresses transmitted by the superimposed rocks. The high smectite content found in the Argille varicolori clays outcropping in San Leo justifies a ductile behaviour of the substratum. In fact the presence of this mineral is always associated with high absorption of meteoric water accompanied by swelling and softening, leading to a progressive decrease of the shear strength parameters. The central part of the slab, where the deep-seated settlements are more intense shows a wide trench, laterally limited by antithetical fractures, which emphasize its wedge-shaped form (Fig. 5).

Remedial measures have been carried out prevalently along the NE margin, underneath the castle and in correspondence with the central lowered area, where the village historical centre is concentrated. The differential movements that affect this central area, with an important lateral spreading component, are witnessed by numerous tension cracks in several buildings which entail continuous restoration works. Nevertheless, the consolidation measures carried out so far seem to be insufficient, especially for what concerns the upgrading of the hydrological conditions. The installation of more effective drainage systems, set up deep at the rock/soil contact, could considerably decrease the porewater pressures in the underlying materials and consequently reduce the earth flows rate of movement, since the high smectite content of these soils make them particularly prone to plasticisation.

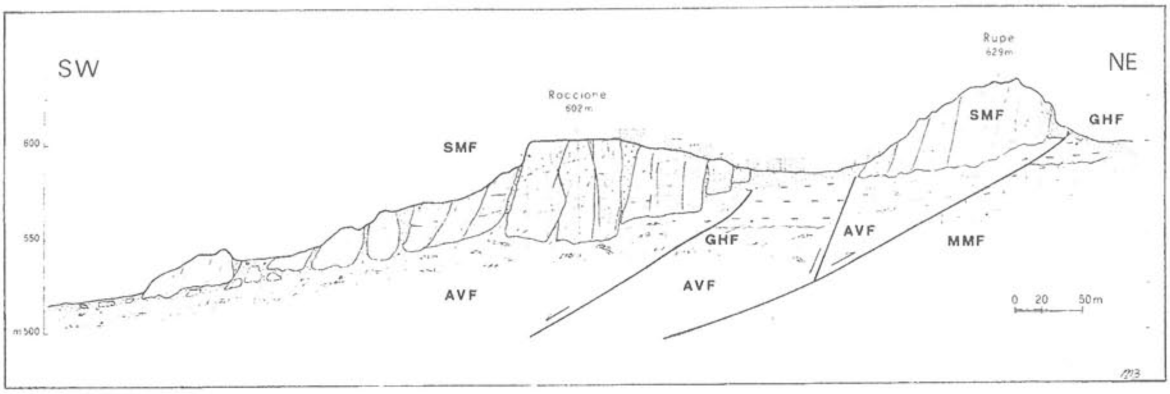

Fig. 6 - Geological section of Pennabilli. AVF = Argille Varicolori Formation (Upper Cretaceous-Lower Eocene): high-plasticity overconsolidated and fissured clays and clayshales; MMF = Monte Morello Formation (Lower-Middle Eocene): marly limestones, calcarenites and marlstones; SMF = San Marino Formation (Lower-Middle Miocene): organogenous limestones; GHF = Ghioli di Letto Formation (Upper Miocene): low-plasticity pelites (after *Conti & Tosatti,* 1993a).

5. SLOPE INSTABILITY IN PENNABILLI (PROVINCE OF PESARO-URBINO)

Pennabilli is an ancient village rising on top of two intensely fractured rocky plates called Rupe (629 m) and Roccione (602 m) in the valley of the River Marecchia (Province of Pesaro Urbino, central Italy). Similarly to other historical centres of this region, such as San Leo, Torriana and Verucchio, also Pennabilli has suffered from the presence of complex landslides favoured by the superimposition of competent rocks on shaly clayey soils. The mass movements, in great part still active, put in jeopardy the stability of many monuments and historical buildings.

The geological setting in Pennabilli is given by two large slabs of organogenous limestones, belonging to the San Marino Formation (Lower-Middle Miocene), which in the southern part directly overlie polychromic clays of the Argille Varicolori Formation, whilst in the northern one they overthrust the Upper Miocene pelites of the Ghioli di Letto Formation (Fig. 6).

The calcareous slabs are affected by three main fracture systems derived from the tectonic phases developed during the Apennine orogenesis. The numerous structural discontinuities have been reactivated by landslides and the consequent differential movements have caused several tension cracks in most of the old village buildings.

The highest concentration of slope movements is found along the southern margin of the two plates, where more accentuated deformations are recorded owing to the presence of the highly deformable polychromic clays. These deformations affect also the overlying calcareous rocks which, deprived of their support, are subjected to extensive falls.

The intensity of gravitational deformations is more limited in the northern sector, where the more competent formation of the Ghioli di Letto pelites makes up the substratum. The different evolution of the landslides affecting the two slabs of Pennabilli derives mainly from the different geotechnical characteristics of the two clayey formations of the substratum.

As for the mechanism causing persistent slope instability, the data deriving from direct observations and geotechnical analyses point out a deep-seated origin for the cliffs' portions directly overlying the polychromic clays, owing to the long-term plastic-viscous deformations affecting this substratum (*Conti & Tosatti,* 1991 and 1993a). A more advanced stage of dismembering is in fact recorded at

Roccione (Fig. 6), where several cavities, ascribable to recent formation rock cracks, are present. The general slope movements correspond to lateral spreads, while at the foot of the slabs the erosive action of meteoric waters, only partially collected and drained, accentuates the instability trend of these cliffs.

Owing to the historical and artistic importance of its buildings, Pennabilli has benefited from an emergency aid programme, directed to the conservation of the historical centre. Geognostic investigations consisting of borings and monitoring surveys of the tension cracks were carried out between 1979 and 1984, after having equipped the buildings with fissure metres and strain metres. These instruments have given some important information on the general trend of these movements, although the period of observation has been extremely limited. The tendency of these cliffs is in fact given by a prevalent dismembering process, that takes place through alternations of extensions and contractions along the rock fractures. The maximum value of displacement are 5 to 8 mm/year for the extension movements and 3 to 5 mm/year for the contraction ones. The phenomenon seems to be related to the rain fall trend, concentrated in the autumn-spring period while the summer is characterised by a long dry spell. Other large cracks and cavities are found along the southern flank of Roccione; they have undergone width variations up to a few dm during the last 30 years and bear a clear witness of the progressive collapse affecting these calcarenitic boulders. The first set of measurements collected so far would confirm the great importance of percolation water in accentuating the rate of movement of these gravitational deformations.

6. THE CLIFFS OF SASSO DI SIMONE AND SIMONCELLO (PROVINCES OF AREZZO AND PESARO-URBINO)

The mountain cliffs called Sasso di Simone (1204 m) and Simoncello (1221 m) rise along the watershed dividing the Marecchia and Foglia valleys, on the border between Tuscany and Marche (central Italy). Their tabular shape is a dominant feature in all the region and represents a landmark visible from long distances (Fig. 7). These two plates are made up of fossiliferous limestones belonging to the San Marino Formation (Lower-Middle Miocene), that extensively outcrops also in the adjacent River Marecchia valley. Sasso di Simone and Mount Simoncello are the remnants of a vast calcareous shelf deposited in a shallow marine environment in the area now corresponding to the high Tyrrhenian Sea and subsequently shifted on top of the Ligurian allochthonous Units toward the Adriatic domain during the Upper Miocene-Lower Pliocene. The intense tectonic stresses associated with the orogenetic movements of the Northern Apennines have caused the subdivision of the original calcareous shelf into several dismembered blocks, most of which have been totally dismantled by weathering and erosion.

The substratum of these limestone slabs corresponds to an olistostrome composed of polygenic clayey breccias (Upper Eocene-Oligocene) derived from submarine mud flows and debris flows detached from the fronts of the advancing Ligurian thrusts (*Conti & Tosatti*, 1993b). In the study area the polygenic breccias unconformably overlie the Ligurian polychromic clays of the Argille Varicolori Formation (Upper Cretaceous-Lower Eocene).

Sasso di Simone and Mount Simoncello are affected by two main sub-vertical fracture systems, and other secondary ones, that totally subdivide the cliffs in their whole thickness. The fractures are progressively more opened toward the top and, laterally, toward the outer less confined margins (Fig. 7).

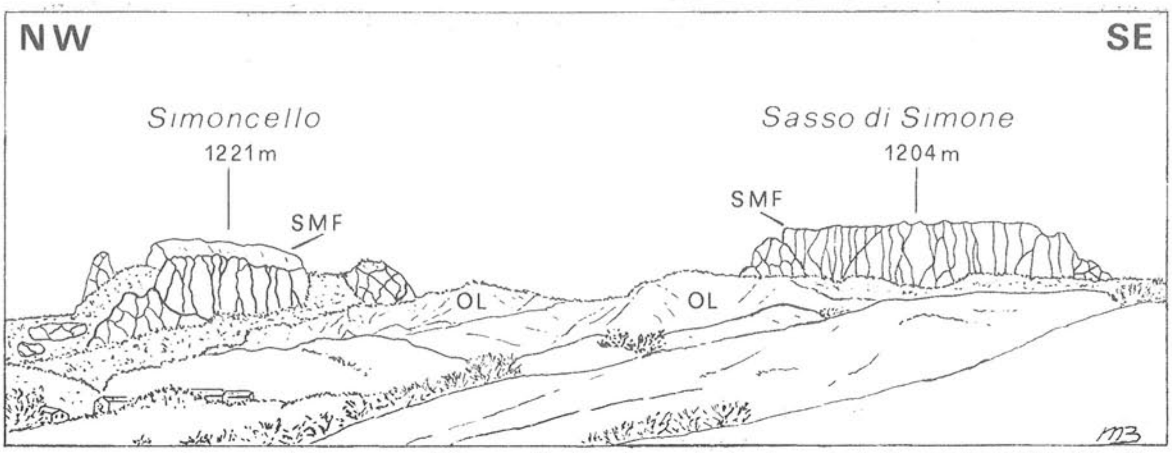

Fig. 7 - Sketch of Sasso di Simone and Simoncello showing main fractures and dismembered blocks. OL = Olistostrome (Upper Eocene-Oligocene): low-plasticity clayey breccias; SMF = San Marino Formation (Middle Miocene): organogenous limestones.

Also in this case, like in the previously discussed situation of Pietra di Bismantova, the structural discontinuities have been remobilised by numerous slope movements, although the rate of evolution of the landslides in the two slabs examined is different, with Mount Simoncello showing a more advanced stage of collapse, as witnessed by the landslide heaps scattered around its margins. At present, the movements are more active along the cliffs' southern sides, where vast earth slides and flows depart from the rock margins, carrying away large amounts of collapsed blocks and boulders.

The landslides are therefore classified as complex movements, consisting of rock falls and topples in the competent limestones and slides and flows in the clayey substratum, often accompanied by surface creep. The most evident aspect of these deformations is given by rock pinnacles and blocks detaching from the main rock masses. But while Sasso di Simone has kept a general subhorizontal strata attitude, Mount Simoncello shows the south-eastern portion of its slab markedly tilted, with progressively lowered blocks. This particular gravitational evolution seems ascribable to a marginal block-type rotational slide, with a failure plane affecting also the underlying clayey breccias of the olistostrome.

Laboratory tests performed on olistostrome samples gave a rather limited range of plasticity, compared with that of the underlying polychromic clayshales, thus suggesting that the origin of the clay breccias is not totally ascribable to submarine mud and debris flows developed only in the Argille Varicolori formation, but also to the supply of more clastic and silty deposits.

The case of Sasso di Simone and Mount Simoncello shows several analogies with Pietra di Bismantova and Pennabilli: presence of open fractures, trenches and lowered marginal blocks, with a general extension towards the less confined edges by means of lateral spreading. Although a deep-seated mechanism has been attributed to the inner portions of the slabs, with basal rupture in the clayey breccias owing to the exceeding of the substratum's bearing capacity (*Bertocci & Casagli,* 1992; *Various Authors*, 1993), there is no clear evidence for such a mechanism, also because the central parts of these cliffs do not show more pronounced settlements. Lateral spreading seems rather caused by extension stresses, similar to the phenomena observed at Pietra di Bismantova (*Conti & Tosatti,* 1993c).

The latest most active period for the vast earth flows departing from the southern margins, which stretch for a maximum length of over 4 km each, reached its peak in the XVII century, probably in correspondence with a marked worsening of the climate that induced the garrison troops defending the Sasso di Simone stronghold to abandon forever this rugged place (*Veggiani*, 1970 and 1992).

7. CONCLUSIONS

After the first six years of research on complex gravitational slope movements in the Northern Apennines it is possible to make some considerations on the causes and deformation mechanisms affecting competent rock plates overlapping weak substrata.

The structural analysis of joints and discontinuities points out a tectonic origin for the main fracture systems surveyed: they correspond to the directions of the principal orogenetic stresses that have determined the overthrusting and piling up of the Apennine formations. Gravitational movements affecting these plates, mainly in the form of lateral spreads, have acted along pre-existing weaker surfaces, subdividing the slabs into several released blocks, subjected to independent movements.

As for the mechanisms causing the persisting instability of the rocky slopes, the investigations carried out so far in sixteen different situations (Fig. 1) do not always confirm the presence of generalised accentuated settlements in the inner blocks of these plates, due to more intense ductile deformation and squeezing out effect induced by high load stresses, rather than along the margins, during the early stages of failure. In two of the cases considered (Pietra di Bismantova and Pennabilli) the substratum is partially made up of rocks showing a degree of competence incompatible with plastic-viscous settlements.

Also within the weaker argillaceous formations, namely Argille a Palombini and Argille Varicolori, a wide range of variability of geotechnical parameters, deriving mainly from the different content of smectite-group minerals, is observable. For example, in samples of the Argille Varicolori clayshales collected in San Leo, the liquid limit w_L is over 110% with plasticity index $I_P > 80\%$, whilst in Pennabilli, Pietra di Bismantova and Semelano w_L is 50 to 60% with $I_P \cong 30\%$.

Mineralogical analyses have confirmed for the high liquid limit and plasticity index in San Leo a prevalent content of calcium and sodium smectite, characterised by high cation exchange capacity and plasticity. Instead, in the other situations examined, the presence of smectite is not prevalent.

Moreover, it has been possible to ascertain for the argillaceous rocks making up the competent slabs' substrata, a marked difference in the geomechanical behaviour according to the *in situ* conditions. In the Argille Varicolori and Argille a Palombini clays, undisturbed samples taken by means of borings and excavated blocks in soil pits at a depth of a few meters show a much higher competence than the same materials collected by the surface, allowing them to be classified as rock shales, according to *Morgenstern & Eigenbrod* (1974). Instead, the outcropping argillaceous rocks show high absorption potentials of free water with consequent volume increase and soil plasticisation. Thus, also the shear strength parameters greatly vary according to the *in situ* state.

Quite different is the mechanical behaviour of other substratum formations such as the Sasso di Simone and Simoncello clay breccias and the Ghioli di Letto pelites outcropping in Pennabilli and Rocca Pratiffi: the former give w_L values of 57 to 65% with I_P of 31 to 38% and the latter show w_L ranging from 30 to 45% with I_P of 18 to 30%. These data are in agreement with a reduced percentage of clay minerals and with geotechnical characteristics corresponding to low-middle plasticity soils, subjected to a limited deformability (*Conti & Tosatti*, 1993a).

Deep-seated deformation mechanisms are therefore justified only when the mineralogical and geotechnical characteristics of the substratum rocks are compatible with a ductile behaviour. Out of the cases previously illustrated, only Acquaria and San Leo seem to fit entirely in this kind of failure model. In Pietra di Bismantova and Pennabilli the substratum is not homogeneous and the rock plates' rate of displacement varies conspicuously from one side to the other. In Sasso di Simone and Simoncello the substratum is homogeneous, but the clay breccias range of deformability appears too limited to justify widespread extrusion of deep-seated materials towards the less confined margins (*Various Authors*, 1993).

Without excluding the occurrence of depth-creep phenomena governing the long-term mechanical behaviour of substratum argillaceous rocks (*Ter-Stepanian*, 1992), the surface processes that lead to pronounced softening and high erodibility conditions in some of these materials seem to prevail in causing and retaining persistent instability conditions in complex geological situations.

Deformations are usually more pronounced not in the central portions but along the margins of the rock plates, where the high erosion rate in the underlying soils is responsible for the undermining of the overstanding rocks.

The prevailing lateral spreading movement recorded in the cases discussed is therefore ascribable to the dominant extension effects along the cliff edges, due to the release of horizontal stresses, rather than extrusion phenomena deriving from more pronounced deep-seated settlements in the inner parts.

Finally, the importance of percolation water in accentuating the rate of slope movements should not be underestimated: it increases porewater pressure within the fractured rocks and soil plasticisation in materials already characterised by low shear strength parameters.

The considerations so far expressed on the numerous interplaying factors that cause slope instability, should point to a cautious attitude before ascribing complex mass movements to simplified models of failure; always remembering that similar morphological features can very often be the result of tectonic and gravitational processes alike, both leading to evolutive geomorphological convergence.

Further original contributions to the study of complex gravitational movements could derive from the acquisition of more accurate data on the mechanical characteristics of the rock masses involved in these deformations. This would require a wider use of soil exploration methods, such as boring and sampling, in order to collect undisturbed material, although the first limit to this kind of investigation is given by its high operating costs. Instead, new quantitative data on the rate of these displacements will hopefully derive in the near future from the Global Positioning System, a new high precision satellite-based monitoring system of sample areas.

Only the correct interpretation of the dynamic mechanisms and the precise identification of the rock volumes actually involved in complex gravitational slope movements will allow the hazard posed by these situations to be properly assessed and eventually mitigated.

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