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Flow slide movements in clayey terrains of the Italian northern Apennines

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Abstract In the clayey terrains outcropping in the Pesaro-Urbino area (central-eastern part of the Italian Apennines), we considered 30 flow-type slide movements. These affected some mainly clayey marine sediments of the Messinian Pliocenic age along with the Cretaceous-Oligocenic clays of the Chaotic clay complex. The mineralogical composition of these three geologic units, the texture, the plasticity and the presence of swelling terms, are all peculiarities, clearly identifiable in the studied clays. The flow slide movements, either active or quiescent, can be connected to the geological history of the clayey outcrop areas. Some morphological and evolved characteristics, typical of each geological formation affected by flow slide movements, have been singled out after repeated study of aerial photos of similar situations, taken within a period of 36 years. The flows are related to the geotechnical characteristics of the clays and to the situation morphometries.

INTRODUCTION

One of the most promising and open fields of research is certainly the study of geomorphic flows. Two main types of factor affect the kinematic characteristics, the evolution, the hydrological conditions and the morphometric features of flow slides: intrinsic factors include the climate, nature and composition of the sediments together with their mineralogical, geotechnical and hydrogeological features. Extrinsic factors are present in each flow slide and require observation of the morphometric features of the area where the slide movement has taken place. Among these factors are the width and form of the valley, the flank slope and the stream depth, the depletion zone, the accumulation zone and the morphology the flow will assume. Thus we can distinguish transient flows from steady ones (D'Elia & Tancredi, 1979), or the main evolved characteristics of these phenomena (Canuti *et al.*, 1988; Iaccarino, 1990). Common to these phenomena is the presence of two side grooves parallel to the slide channel. Such grooves will form several other streams, mostly active during the rainy season. Erosion and drainage cause morphometric and hydrological alterations inside the flow, thus influencing its development, and behaviour. These events take place, even if there is no possibility of new depletion.

The mechanical behaviour of the clays, including the consolidation and reconsolidation phenomena (Mesri & Castro, 1987; Jamiolkowski *et al.*, 1983) due to the mass movements, as well as the effects of release of tension, thixotropy, sensitivity, microstructural observations and the heterogeneity of the sediments add to the difficulty of explaining flow-slide behaviour. It is now clear that the interpretation of so many interacting factors cannot find any practical resolution if not by means of numerous statistical analyses (Dovzak & Frassoni, 1990). This research supplies objective comparison of 30 flows, in order to identify common factors and to form a model of the observed processes.

GEOLOGICAL, MORPHOLOGICAL AND CLIMATICAL FEATURES

The Pesaro-Urbino area, in central-eastern Italy, is located between the Apennine ridge and the Adriatic sea (Fig. 1). Here the outcropping formations can be classified in three main geological areas: the marine deposits of the Umbro-Marchean sequence (upper Triassic-Miocene), the deposits of the Plio-Pleistocene sequence, and the Chaotic clays complex in the Marecchia Valley (Cretaceous-Oligocene).

The unit of the Umbro-Marchean series examined in this study is the Messinian Colombacci formation. Its sedimentation features several local cycles; each cycle typically comprises units from sandstones, often amalgamated with silty clays. The "Colombacci" of evaporite origin, are typical of this formation. They are clear-coloured, calcareous layers with plane parallel lamination.

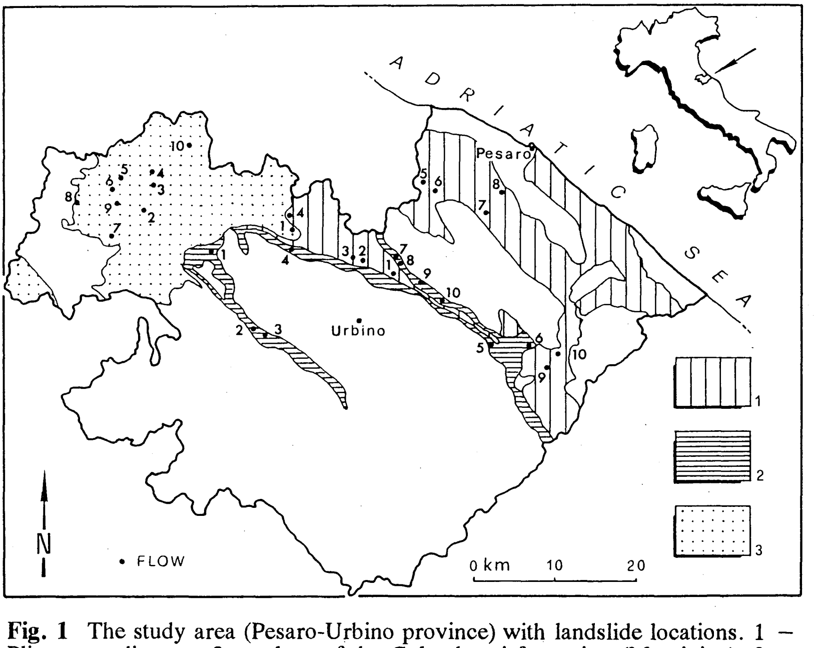

Fig. 1 The study area (Pesaro-Urbino province) with landslide locations. 1 – Pliocene sediments; 2 – clays of the Colombacci formation (Messinian); 3 – Marecchia Valley clays (Cretaceous-Oligocene).

The depositional environment was that of a basin lagoon, characterized by low salinity and protected from the real marine environment. It formed due to the advance of the Apennine chain, and to the salinity drop that occurred in the whole Mediterranean basin. In the upper part of the early Pliocene, the compressive tectogenesis reached its maximum activity in the Pesaro-Urbino areas. This caused the formation of elongate depressions (northwest-southeast) where several overlapping turbiditic materials settled (Boccaletti *et al.*, 1986). These deposits comprise two different lithofacies which are often intercalated; one mainly sandy and the other one clayey. The settling environment was that of the deep sea.

Also, during the early Pliocene, the last settling phase of the "allochthone complex", in the Marecchia Valley sheet took place in the northwest of the Pesaro-Urbino province. Owing to tectonic effects it converged to a transverse depression following the classical process consisting of compression plus sliding (Ricci Lucchi & Ori, 1985). The above-mentioned sheet is a heterogeneous assembly of edges of different late Cretaceous to late Oligocene sedimentary formations.

The terrains examined in this study form the "Undifferentiated Complex", which represents a combination of disorderly allochthone units which cannot be classified. Their composition is a random mixture of shales and reddish, greenish or greyish marls incorporating calcareous and calcarenitic fragments of various dimensions, and they are characterized by an extended schistosity making the terrain a composition of small glossy scales (Ruggieri, 1970). Slide flow movement (Fig. 1) regularly occur in mainly clayey, and sometimes marly or siltitic clay terrains.

The morphology of the Pesaro-Urbino area features a clear contrast between the mainly mountainous western zone and the hilly zone stretching eastwards to the Adriatic coast.

The first zone is characterized by relief higher than 1000 m, aligned in the northwest-southwest direction; whereas the second presents a much smoother landscape, sometimes interrupted by low ridges. The Marecchia Valley area, by contrast, is marked by a peculiar morphology: the landscape is typically made up to low hills with gentle slopes, punctuated by isolated and hazardous reliefs of allochthonous lithoid composition.

All over the territory in the outcrops of clayey terrains are badlands, especially in the Chaotic clay complex, but less so in the other pelitic units. Lateral spread phenomena are also widespread; they can be found in the Chaotic clay complex, where some allochthonous bodies of fractured limestones (Bertocci *et al.*, 1991; Cancelli & Pellegrino, 1987) are placed over plastic clays. On the other hand, the same phenomena of lateral spread in stiffer geologic formations bearing on plastic clayey sediments (Gori & Veneri, 1992) or in sandy Pliocene bearing on clayey are still present.

In the study of a complex topic like the evolution of gravitational flow phenomena, references to rainfall in general and to the regime of pore pressures within the slide bodies (Hutchinson, 1970), are extremely relevant. In this case, the only data available are rainfall records (Fig. 2). There are no

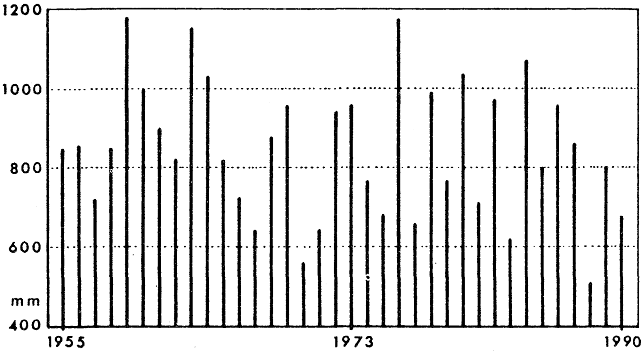

Fig. 2 Annual precipitation (mm) from 1955 to 1990.

data on the variations of the pore water pressures in the flows, because the examined period is too long (1955-1991) and because it is difficult to install instruments in such unstable areas. Such limitations permit only a qualitative comment on the rainfall data which do not show any correlation between rainfall and evolution of the phenomena. The Pesaro-Urbino area is subjected to considerable climatic variations (Fig. 3), as it lies between the Adriatic sea on the eastern side (marine climate) and the Apennine ridge on the western side (apennine climate). During the winter snow remains for several weeks above 500 m above sea level, whereas spring thaw and rainfall cause new landslides or reactivate palaeoslides.

MINERALOGICAL AND GEOTECHNICAL FEATURES

Table 1 shows the mineralogy composition of the three clay units described previously, with a total absence of calcite and dolomite along with an abundance of phyllosilicates and accessory in the Chaotic clay complex.

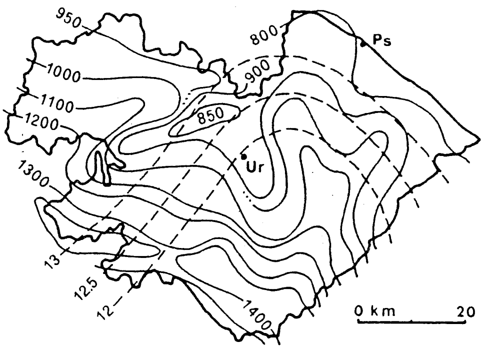

Fig. 3 Map of the Pesaro-Urbino province, with average annual rainfall (mm) and temperature (°C).

The Pliocenic and Colombacci clays on the other hand, show a similar composition. The Chaotic complex clayey fraction (Table 2) shows a considerable amount of smectites and kaolinite and a notable presence of illite-smectites.

Illite and chlorite are quite scarce. The Pliocenic clay contains the clay components in almost equal percentages. The difference in the Colombacci clay formation is due to the abundance of smectites and the absence of illite-smectites. The physical and petrographic significance of the above-mentioned data is discussed by Gori & Vannucci (1987).

Table 3 lists the geotechnical properties of the clays. The shear tests used consolidation load values lower than 200 kPa at a deformation speed of 0.005 mm min^{-1}. The C_v values had σ_v = 100 kPa.

Both the Pliocenic clay and the Colombacci clay formation had regular mechanical behaviour. In the Chaotic clay complex, however, because of the peculiar structure and the higher activity and plasticity, there is scatter of the physical parameters. This phenomenon can also influence the residual shear resistance (Gori, 1989).

Table 1 Mineralogical composition: 1 – Chaotic clay complex; 2 – Pliocene clay; 3 – clays of the Colombacci formation.

Sample	Quartz	Potassium feldspar	Plagioclase	Calcite	Dolomite	Phyllosilicates + accessory
1	17.0%	8.0%	3%	-	-	72%
2	9.0%	2.0%	4%	35%	5.0%	45%
3	9.6%	4.8%	2%	36%	2.6%	45%

Table 2 The argillaceous mineral components (for samples 1-3 see Table 1 heading).

Sample	Illite-smectites	Chlorite	Smectites	Kaolinite	Illite
1	15%	traces	50%	30%	5%
2	10%	20%	25%	25%	20%
3	-	15%	60%	10%	15%

MORPHOLOGICAL EVOLUTION

We observed 30 flows, 10 of which are present in the Chaotic clay complex, 10 in the Colombacci clay formation and the remainder in the Pliocenic clay. We chose only the slides having common or comparable characteristics such as: use of the soil (untilled or only partially cultivated), slope dip (between 14° and 20°), exposure (mostly to the south) and altitude (200-500 m above sea level), in order to compare the physical phenomena under examination.

We used aerial photos covering a 36-year-long period to carry out a time control on the flow evolutions. For the most interesting areas, we examined the 1:10 000 scale images dating back to 1955-1973-1991, which were adequately

Table 3 Geotechnical data – all values are averages. See Table 1 heading for definition of samples 1-3.

Sample	Sand (%)	Silt (%)	Clay (%)	Wl (%)	PI (%)	A	γ (kN m^{-3})	W (%)	ϕ' (x°)	ϕ'_r (x°)	c' (kPa)	c_r (kPa)	C_u (kPa)	C_v (cm^2 s^{-1} 10^{-4})
1	2	18	80	99	60	0.75	21.2	35	28	15	6	4	180	33.0
2	2	53	45	42	19	0.42	19.8	26	26	18	8	2	120	3.2
3	4	54	42	50	26	0.62	20.3	27	30	16	6	2	135	4.5

Symbols and units follow the ISSMFE recommendations as given in the *Proceedings of the 9th ISSMFE International Congress* (Tokyo 1977), vol. 3, 156-170.

complemented by field surveys. The observations that are presented do not represent a "continuous" vision of the described phenomena, they only produce an evaluative analysis of three distinct periods, which are not necessarily connected to the real partial movements that occurred in the course of time. The temporal comparison analysis concerned both the active and the quiescent flow, the formation of active or quiescent complex slides, the presence of

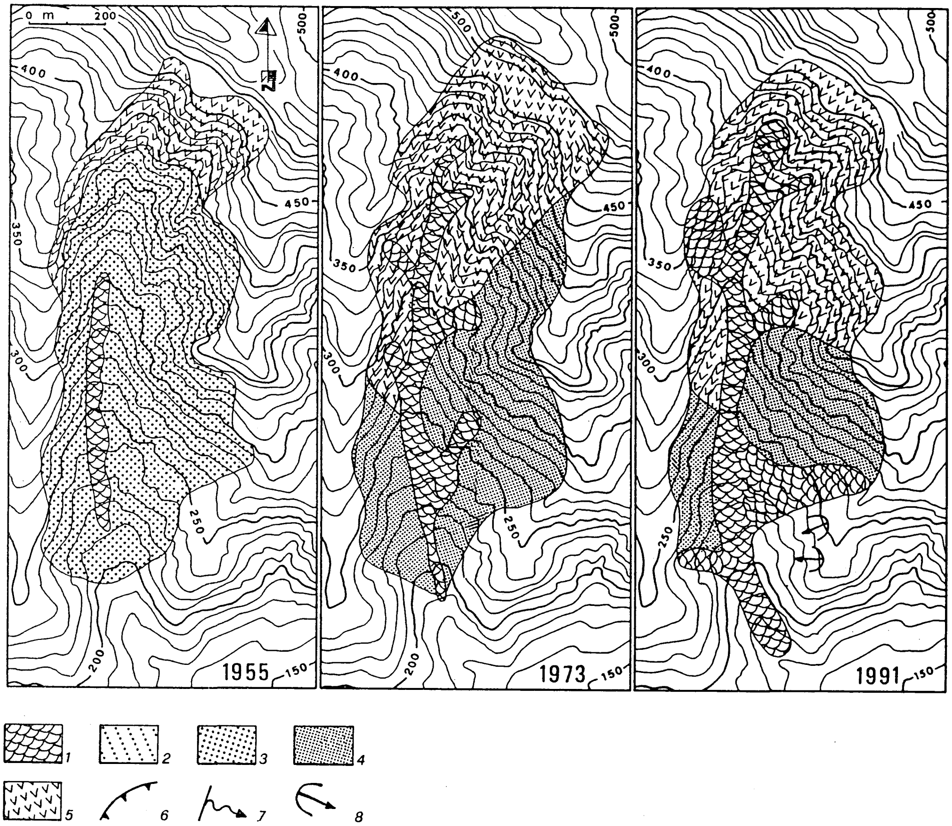

Fig. 4 Temporal evolution of flow movements in the Chaotic clay complex. 1 – active flows; 2 – inactive flows; 3 – active complex landslide; 4 – inactive complex landslide; 5 – badlands; 6 – edge of erosion escarpment; 7 – creep deformation; 8 – landslide not to scale.

debris accumulations, slopes and active or quiescent crowns, as well as the identification of active depletion areas and badlands evolution (Fig. 4). In order to simplify the explanation, the terms "flows" is broadly interpreted to include mud-flows, earth-flows and debris-flows (Varnes, 1978), as the clayey fraction, though varying, generally represents a very important content. Figure 4 shows a comparison of the Chaotic clay complex time-flow evolution. On the ordinate are values in m^2 relative to the surfaces directly affected by the active flows. In this case we can notice an increase of all active and unsettled surfaces in the period from 1973 to 1991. In some rare cases some slide movements taking place in 1955 undergo some partial inactive phases, so that the extent of the movement decreased. In the Chaotic clay complex slides there is an evolution of complex slides (caused by the heterogeneity of the sediments involved and linked to the presence of allochthones, among which some are hard rocks), turning into flow movement. The depletion zones are extended and tend to change into badlands. Flows overlapping each other are not clearly evident; on the other hand significant active lateral supplies are very common, thus giving flows digital aspect. The most common morphometries do not have the typical long shapes; they usually have an extension equal to 20×10^{-4} m^2 and higher width dimensions, in comparison with those of the slip valley channel. The Pliocenic clay flows are completely different as they develop always within the same valley-channel, and have a regular long shape. Overlapping phenomena are very frequent and their extent is much more restricted. There are no side supplies from the valley slopes and the feed comes only from the detachment crowns. Stream incisions parallel to the slide channel, close to the two external flanks, are very evident. Alternating patterns of activity and quiescence are found in up to the morphologic heights where quiescence is more frequent (Fig. 5).

The morphology and evolution of the flows seem to have developed in an intermediate period, that is between the two clayey formations. However, we must underline the fact that during the examined period (1955-1992), the tendency to inactivity is mainly around 1973 (Fig. 6).

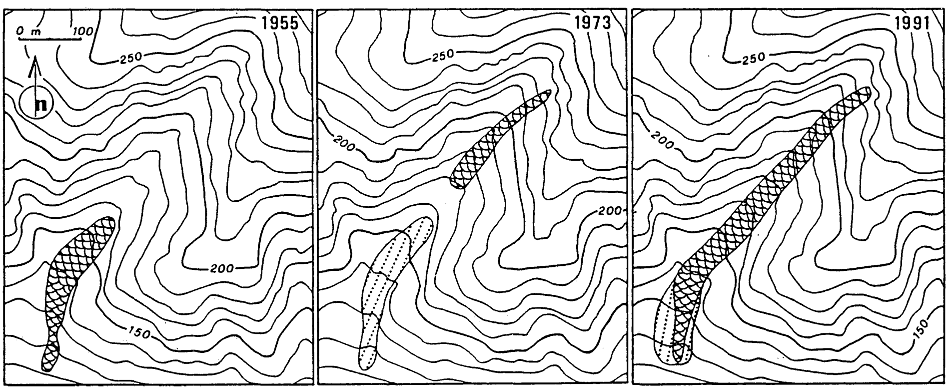

Fig. 5 Temporal evolution of flow movements in Pliocene clayey sediments.

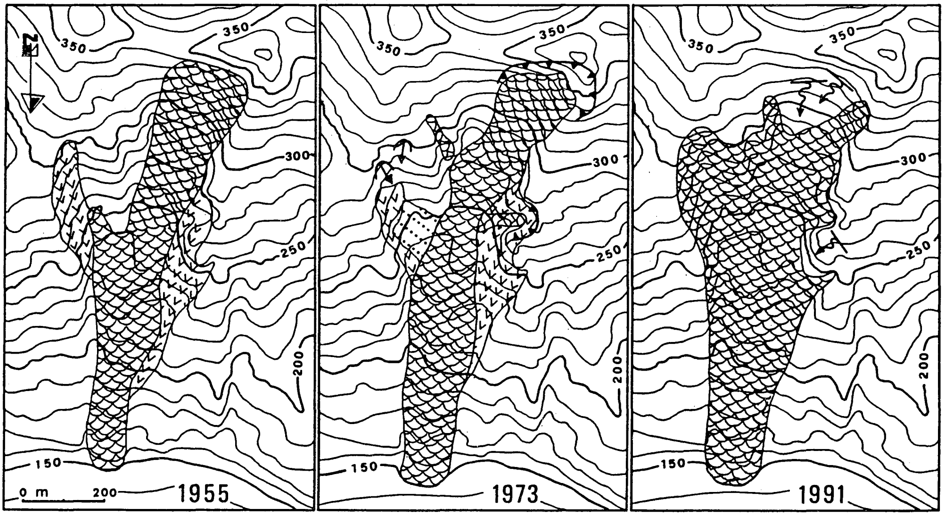

Fig. 6 Temporal evolution of flow movements in the clays of the Colombacci formation.

CONCLUSIONS

The data presented, although from a restricted sample of 30 slide events, enable us to single out some significant tendencies concerning the time-evolution of the flows (Figs 7-8).

Flow evolution is the Chaotic clay complex corresponds to the badlands of at least one flank of the valley, with extended active flow movement often originated by initial complex slides. 73% of the flows developed with valley inclinations higher than 15% and showed continuous increases of the areas affected. The Chaotic clay complex composition seems to be a mixture of very plastic clays (PI = 60%) and swelling minerals constituting a component of over 50%.

Less extended flow evolutions in Pliocenic clay lead to overlapping and covering of previous movements, accompanied by a clear drawdown of the depletion zone, which is always present mainly at the top of the valley. The valley inclination seems to have little to do with the flow evolution phases, as it is represented by varying values (11-23%). The lower plasticity level (PI < 20%) observed in these clays (where CF it is 45%) characterized by a lower activity and swelling minerals less than 30%, limits the unsettlement time progression and gives the flow its typical long shape along with the two clear grooves, close to the slide channel.

Finally, flows in the Colombacci clay formation showed an initial behaviour not much different from the Pliocenic clays flows. The phenomenon later presents some features similar to those of the Chaotic clay complex. This observation can be connected to the medium plasticity (PI = 25%) and also to

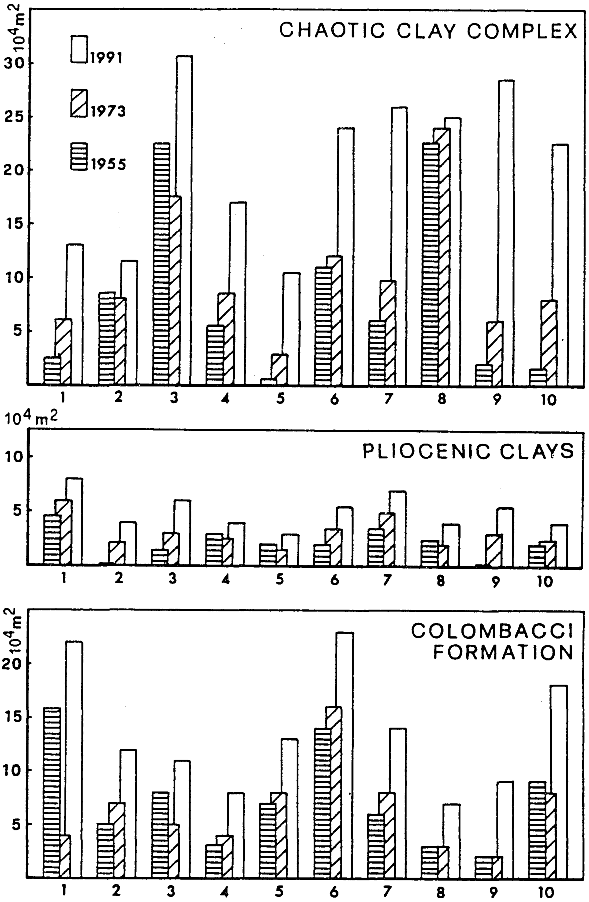

Fig. 7 Histograms of the temporal evolution of active flow movements.

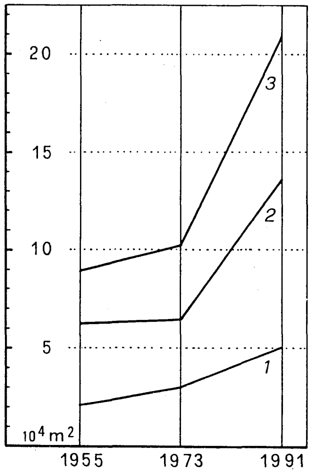

Fig. 8 Average temporal evolution of active flows over 36 years. 1 – Pliocene clays; 2 – clays of the Colombacci formation; 3 – Chaotic clay complex.

the activity of these clays in which swelling minerals were 25% or higher, in comparison to the total clay fraction (equal to 42%). All the phenomena described qualitatively above can be related to geotechnical factors concerning the clay behaviour in shear resistance, viscosity, strength and deformations, as well as in microstructures, primary and secondary consolidation. A further investigation perspective is connected to the current phenomenon of acid rainfall (pH = 4). The effects on the variations in peak and residual shear clay parameters of pH variations, will surely contribute to the modification of the evolutive tendencies as well as the reactivation of slide events, such as flows.

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