MINERALOGICAL AND GEOTECHNICAL CHARACTERIZATION OF STRUCTURALLY COMPLEX FORMATIONS INVOLVED IN THE SLOW-MOVING LANDLIDES AFFECTING THE SOUTHERN APENNINE

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INTRODUCTION

"Slow-moving landslides" are down-slope movements of rock masses, characterized by low rates of displacement (some mm to 0.5 m per year). External phenomena, as long-duration rainfall or earthquakes, can trigger parossistic events, increasing their velocity up to 50 cm/hour-5 m/day, and consequently making them very dangerous. Slow moving landslides usually occur in correspondence of the more weathered and surficial parts of "structurally complex formation slopes". Structurally complex formations are particular type of flyschoid materials, characteristic of Southern Italy, generally subdivided into two groups on the basis of their lithological complexity (Esu, 1977).

This research is focused on the characterization of a slow moving landslide, which in the past was affected by a paroxysmal evolution, adopting a multidisciplinary approach, characterized by combined mineralogical and geotechnical analyses. The objective was to verify if there is a correlation between mineralogical and geotechnical parameters, and if the landslide is associated with a more weathered part of the rock mass.

As a matter of fact, it is generally assumed that the major amounts of expandable clays are associated with highly weathered rocks, and that there is a relationship between these amounts and the shear strength of a rock material. The presence of smectite should favor the water adsorption in the rock and the decrease of its shear strength (Taylor & Cripps, 1987). The transition from the deeper to the more surficial weathering zone is governed by an increase of material degradation.

The object of this study was a particular landslide, which occurred in 1963 in the Sorrento peninsula (southern Italy) involving three different villages where several infrastructures were damaged: Termini, Nerano and Marina del Cantone. The phenomenon was triggered by a long duration rainfall (Cotecchia & Melidoro, 1966).

The material mainly involved in the landslide belongs to the *Arenarie di Termini Formation*, a flyschoid lithotype of Miocene age. This Formation consists of sandstones, rich in calcareous clasts and clays (Iannace *et al*., in press.).

In geotechnical engineering, the relationship between the amount of water in a soil and its mechanical behavior is evaluated by the Atterberg Limits. They represent a basic measure of the critical water contents of a fine grained soil, at which the physical properties of the material changes (*e.g*., the water content at the transition from the plastic to liquid state).

These measurements are also used to obtain indirect information about the mineralogical nature of the analyzed material, through, for example, the so-called Casagrande chart, which allows to determine the types of clays occurring in a rock by comparing Plasticity Index (*PI*) and Liquid Limit (W_L) (Holtz & Kovacs, 1981). Also the Skempton diagram has been widely used in the past. It evaluates the "activity of a soil" (*A*) defined as the ratio between the PI and the clay fraction (*CF*) (Skempton, 1953), subdividing clays into three groups: *Inactive-, Normal-,* and *Active-Clays.* Each category is related to specific types of mineral species, which are characterized by a specific surface area (*SSA*).

Bearing this in mind, the main aim of this thesis was also to test the benefits and the limits of the empirical mineralogical-geotechnical correlation. X-ray Powder diffraction (XRPD) analyses were carried out on several samples, collected from boreholes drilled in the studied area, to directly evaluate the mineralogical composition of the material involved in the landslide. Specific analyses on clay fraction were also performed to deeply investigate the type of possible expandable clays occurring in the rock.

Instead, geotechnical analyses (Atterberg Limits, specific gravity tests and grain size distribution analyses) allowed to directly evaluate the physical-mechanical properties of the landslide and, indirectly, to obtain the mineralogical composition of the samples.

METHODS

The mineralogical and geotechnical analyses were carried out on a set of samples selected from boreholes drilled in the studied area in correspondence of the crown, track, and accumulation zones of the landslide in proximity of Termini, Nerano and Marina del Cantone villages, respectively (Fig. 1). The technical features of the boreholes are reported in Table 1.

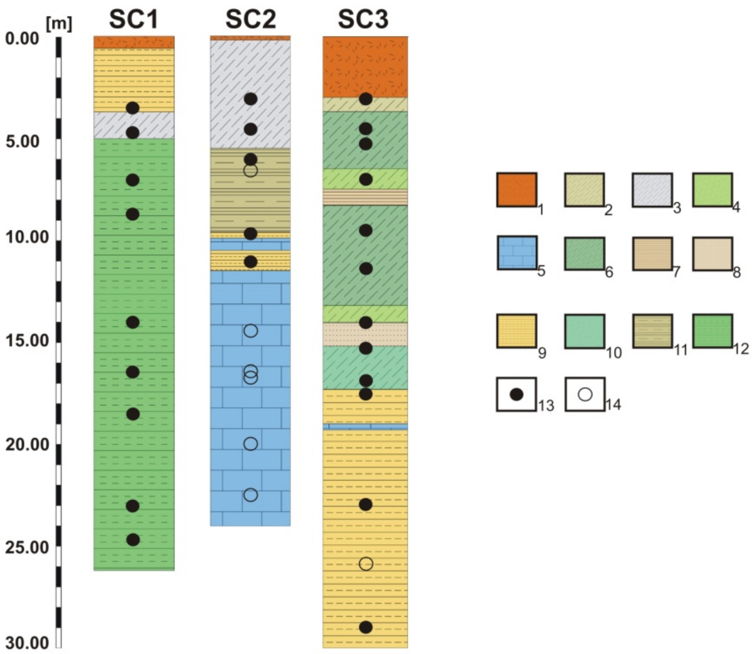

Fig. 1 - Stratigraphic sequences of the studied area: 1) top soil; 2) greyish-green silty shales; 3) shales; 4) greenish silty shales; 5) calcarenitic sandstones; 6) greyish silty shales; 7) brownish silty shales ; 8) silty sands; 9) sandstones; 10) bluish-gray silty shales; 11) greyish clayey silts; 12) marly shales with calcareous clasts; 13) samples selected for mineralogical and geotechnical analyses; 14) samples selected for mineralogical analyses.

Table 1 – Main drill core features.

Locality	ID Core	Sampling	Depth (m)	Instrument	Instrument depth (m)
Termini	Sc1	CC	26.00	Inclinometer	25.00
Termini	Sd3	CD	5.00	Piezometer	5.00
Nerano	Sc2	CC	24.00	Inclinometer	23.00
Marina del Cantone	Sc3	CC	30.00	Inclinometer	29.00
Marina del Cantone	Sd1	CD	30.20	Piezometer	30.00

Note: CC= continuous core; CD= destructive core.

Continuous cores were drilled to obtain information about the main stratigraphic features of the studied area and also for the extraction of disturbed samples for laboratory tests. These samples were selected on the basis of main stratigraphic features and depth (Fig. 1).

Mineralogical characterization of selected samples has been carried out on bulk samples by XRPD. Specific analysis on the clay fraction were carried out on oriented aggregates to obtain information about the particle sizes lower than 0.2 µm. Oriented aggregates were prepared by following the Moore & Reynolds procedure (1997). The comparison between normal, glycolated and heated (370 °C) oriented aggregates allowed to verify the presence of mixed layers illite/smectite (*I/S*) and chlorite/smectite (*C/S*). The grade of ordering of mixed layer *I/S* was also evaluated following the Moore & Reynolds (1997) procedures in order to obtain information about the grade of weathering or diagenesis which affected the material involved in the landslide (Pollastro, 1993). Quantitative characterization has been carried out on bulk samples, using the Bruker TOPAS software. Combined Reference Intensity Ratio (RIR*)* and Rietveld methods have been used for the quantitative analyses. An amount of 20 wt.% corundum has been added to the samples as internal standard. The obtained results were calibrate with the bulk chemistry data (from XRF analyses) through the use of Vb Affina software (Leoni *et.al*., 2008). It allowed to exceed problems due to the presence of poorly crystalline phases, like clay minerals and mixed layer phyllosilicates. It is worth to note that Topas software reaches the best results for the evaluation of materials constituted by strongly crystalline mineralogical phases, whereas in case of clay minerals and mixed layers it evidences some working problems.

The mineralogical characterization of the analyzed samples was also supported by SEM (Scanning Electron Microscopy) images. Several geotechnical analyses (specific gravity test, wet sieve analysis, Atterberg limit) were carried out on some of the selected samples (Fig. 1) to obtain information about the main geotechnical properties. In all cases samples were prepared following the ASTM procedures (ASTM Standards, 1999). Further analysis, such as rheological tests, were carried out on a set of samples, selected on the basis of their mineralogical features, to establish the transformation processes of the materials into flow-like phenomena (Malet *et al*., 2003) on the basis of their yield stress and viscosity.

RESULTS

Material involved in the landslide appears to be mainly constituted by phyllosilicates (mixed layers *I/S* and *C/S*, chlorite, kaolinite, and muscovite), quartz, feldspar (Na- and K-feldspar), and carbonates (calcite and dolomite). Representative XRPD spectra are shown in Fig. 2.

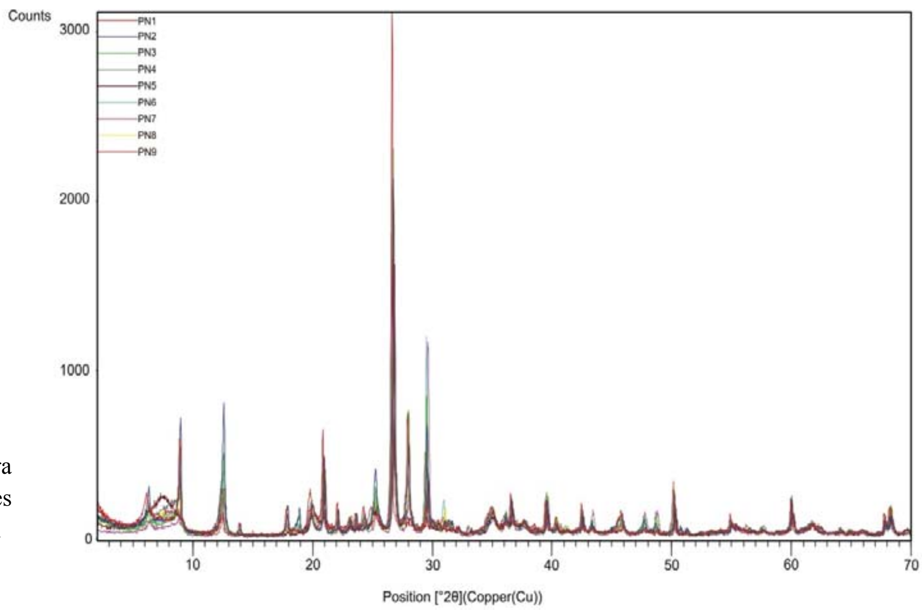

Fig. 2 - XRPD spectra representative of samples collected from the crown zone.

The results obtained by using the Topas software show that the mixed layer *I/S* is the most representative phase, followed by quartz and calcite. It was not possible to evaluate the amount of mixed layer *C/S* because of the impossibility to detect them in the XRD patterns of the bulk samples. Vb Affina software allowed to exceed this problem and to determine that: *i*) the amount of mixed layers I/S ranges between 8 and 52 wt.%; *ii*) the amount of mixed layer C/S ranges between 0 and 15 wt.%; *iii*) the amount of chlorite ranges between 1 and 17 wt.%; *iv*) the amount of kaolinite ranges between 0 and 12 wt.%.

For all detected phases, no particular correlations with depth were observed. By specific analysis on the clay fraction it was also verified that the grade of ordering varies with depth without a specific trend.

Geotechnical analyses were carried to verify possible relationships between the mechanical behaviour of the soil and its mineralogical composition. The main obtained values are reported in the Table 2.

Table 2 - Minimum, maximum and average of main geotechnical values.

	ϒs (kN/m^3)	W_L %	W_P %	IP %	% Gravel	% Sand	%Silt	% (CF)
MIN	25.9	24.2	18.4	3.3	2.2	23.5	15.7	4
MAX	27.5	49.4	32.7	22.5	51.5	53.8	45	22.5
AVG	26.7	36.9	23.3	13.8	20.5	35.8	29.4	14.8

Note: ϒs = specific gravity; WL = liquid limit; WP = plastic limit; IP = plastic index; CF = clay fraction.

Considering the Casagrande chart, the analyzed samples were categorized as "inorganic silt and organic clays" and "medium plasticity inorganic clays" (Fig. 3). In this study the mineralogical compositions, evaluated by using the Casagrande chart and the Skempton diagram were compared with the mineralogy directly obtained by XRPD quantitative analysis.

On the basis of the empirical classification mentioned before, the samples should be mainly constituted by illite and kaolinite. No information about the presence of mixed layers *I/S* and *C/S* can be obtained by using these methods.

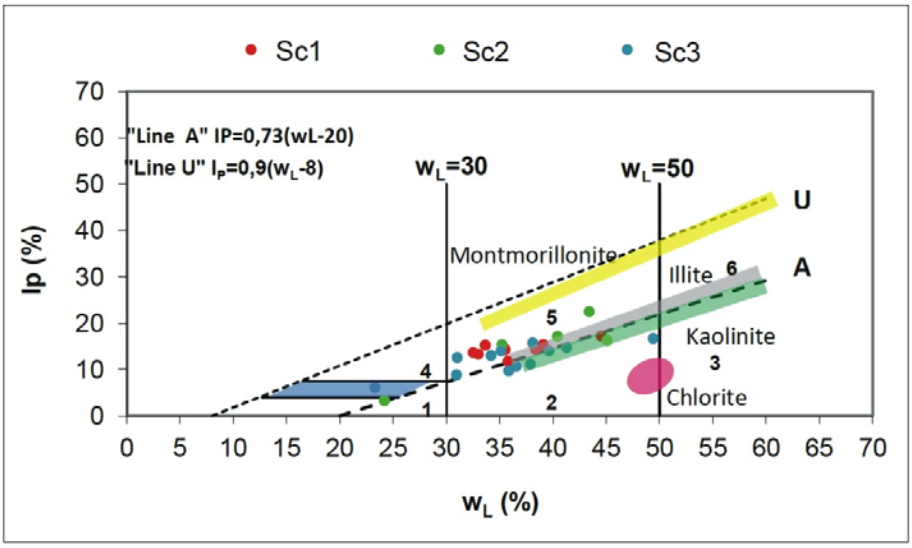

Fig. 3 - Casagrande chart: 1) Inorganic silts, low compressibility; 2) Inorganic silts and organic clays, medium compressibility; 3) Inorganic silts and organic clays high compressibility; 4) Inorganic clays, low plasticity; 5) Inorganic clays, medium plasticity; 6) Inorganic clays, high plasticity.

The rheological analyses confirmed that the rate of movement of this landslide is variable. The flow behavior of the material involved in the landslide is pseudo-plastic with yield point (Schramm, 1998). This means that, according to literature, the first stage of movement is connected to slow plastic deformation, and that, after the yield point, the same material starts to flow, due to a viscosity decrease (Fig. 4). In fact, it results that the lower the viscosity, the higher the rate of movement. These data agree with the main feature of the slow-moving landslides, which usually start to flow after triggering events.

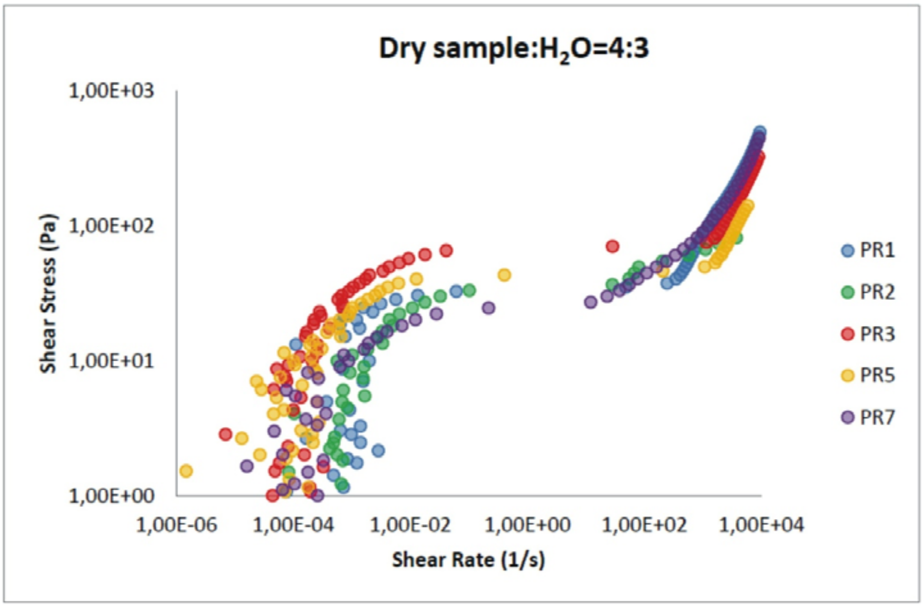

Fig. 4 - Rheological analysis diagram considering the amount of water lower than the amount of specimens, performed on samples collected from the sliding zone.

CONCLUSION

The rocks involved in the Termini Nerano landslide can be considered a structurally complex Formation of the highly heterogeneous type. It was not possible to correlate neither stratigraphic nor mineralogical features between drillcores, although all analyzed samples belong to the same Unit (Membro delle Arenarie di Nerano) (Iannace *et al.*, in press). The presence of mixed layer *I/S* with different grade of ordering not continuously varying with depth indicates that the considered material is highly over-consolidated and then it cannot be associated with a weathering profile.

This research also highlighted the major limits in the use of empirical geotechnical relationships for clay-type determination. Comparing the mineralogical data obtained by empirical method with those obtained by direct XRPD analyses, it has been verified that in most of cases they do not match. As shown in the previous paragraph, by considering Casagrande chart and Skempton diagram, the analyzed samples should be mainly constituted by illite and kaolinite. By direct XRPD analyses, it has been instead verified that samples always contain illite but into mixed layer *I/S*, and that kaolinite is very rare. It has been evidenced that: *i*) in the first case, the empirical methods straightly simplify the mineralogy of the samples, not allowing to evidence the occurrence of the mixed layer containing smectite; *ii*) in the second case, they produce completely wrong results. Consequently, from this study it is clear that the coexistence of different mineralogical phases (*e.g.*, clays, quartz, feldspars, and carbonates) with different *SSA* makes probably useless the use of Casagrande chart and Skempton diagram whereas in soils mostly constituted by clays minerals Atterberg limits and direct mineralogical analyses (*e.g.*, XRPD) should produce more coherent and comparable results.

Moreover, a few samples resulted as “not classifiable” in the Casagrande chart and Skempton diagram, because they contained less than 5 wt.% of clay fraction in the sieved analysis, though major amounts of clay minerals were revealed by using XRPD. This evidenced that, in case of high grades of compaction of particles at microscale, the grain size distribution analyses underestimated the real amount of clays.

The high consolidation of the analyzed material produced a strong aggregation between the particles reducing the fraction of loose material in the rocks. Consequently, grain size distribution analyses underestimate the amount of clay fraction relatively to the direct XRPD mineralogical analyses, making difficult to obtain accurate values of the grade of activity of the analyzed material.

Finally, it is necessary to remember that a difference, which has plagued several authors in the past (*i.e.*, Guggenheim & Martin, 1995), exists between the concepts of "clay minerals" and "clay size". Clay minerals are phyllosilicates, characterized by a peculiar mineralogical composition and a particles size below 2 μm. Clay size is a term referred to those particles of a grained loose soil, which are smaller than 2 μm, independently by their mineralogical composition (*i.e.*, these small particles can be constituted not only by clay minerals, but also by fine grained feldspar, quartz, or other minerals). In definitive, when studying this type of geomaterials, it is necessary to kindly use the empirical geotechnical relationships for mineralogical characterization and clay amount evaluation.

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