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Geometric and dynamic properties of landslides in scaly clays in Northern Italy

Propriétés géométriques et dynamiques des glissements dans les argiles écailleuses au nord d'Italie

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ABSTRACT: Over a very extensive area of the Northern Italian Apennines there are outcrops of soils belonging to structurally complex formations. The nature of these varies from clayey to shaly-marly and the shear strength is generally low.

These characteristics cause numerous landslides often large in area and thickness (several tens of metres) and as such deserve scientific and technical study aimed at acquiring a knowledge of their geometry and dynamics.

This paper reports nine cases where monitoring of landslides, carried out using inclinometers, made it possible to ascertain their evolution in terms of displacements, velocity of deformation, the influence of seasonal changes, geometry and geographical orientation.

The landslides were classified according to methods in common use and an analysis of their inclinometric deformation made it possible to identify different failure mechanisms inside the rock mass.

RESUME: dans une région très étendue des Apennins nord (Italie) affleurent des terrains appartenant à des formations à structure complexe dont la nature varie entre argileuse et argilo-marneuse et dont les caractéristiques de résistance au cisaillement sont généralement faibles.
Cettes caractéristiques entraînent de nombreux glissements qui présentent fréquemment une étendue et des épaisseurs élevées (plusieurs dizaines de mètres) justifiant donc l'intérêt technique et scientifique à connaître leur géométrie et leur dynamique.
Notre étude présente neuf cas où le monitoring du glissement, réalisé grâce à des tubes inclinométriques, a permis de caractériser son évolution au niveau des déplacements, de la vitesse de déformation, de l'influence des cycles saisonniers, de la géométrie et de l'exposition. Les glissements ont été classés selon les méthodes couramment utilisées et l'analyse de leurs déformations inclinométriques a permis de distinguer différents mécanismes de rupture à l'intérieur du massif.

1. INTRODUCTION

The outcropping soils in the North Italian Apennines is mainly of sedimentary origin and consists of paleogeographic units that are very different as far as tectonic and geological history are concerned.

During Alpine orogenesis (Tertiary) large masses of sedimentary ground of a predominantly clayey nature were dislocated by tectonic and gravitational forces, in a North Easterly direction, covering and incorporating portions from different units. These masses, which after tectonic dislocation appear more fissile (shaly clay, shale), are extremely heterogeneous with reduced shear strength.

Almost all the hill and mountain slopes where this type of soils is found, present phenomena of instability that fall mainly within the slow to extremely slow range of internal movements (VARNES, 1978).

The dynamic and kinematic characteristics of instability phenomena essentially depend on the geometry of the mass that is moving, on the geographical orientation and on the characteristics of the soils.

A large number of inclinometers were used to monitor slope movements in the nine cases that were studied. The resulting data was processed to give information on the dynamics and development of gravitational phenomena both as a function of seasonal change and over the whole period of monitoring, which lasted several years.

For one of the phenomena observed it was possible to establish correlations between seasonal rainfall measurements and the entity of displacements.

2. GEOLOGICAL SETTING

The instability phenomena under study were located in the North Eastern band of the Apennines where the outcrops mainly belong to the External "Ligurid" Units.

These units are of an allochthonous nature (Fig. 1) and present an extremely chaotic structure due to considerable dislocations that occurred mainly in the Eocene period. The dislocations that occurred were mainly gravitational in nature and were favoured by a plastic level of poor cohesion and by the clayey nature of the ground. The soil is generally classified as "Scaly clays", "Complex chaotic", "Non-differentiated" and "Clays and limestones".

The lithology of the ground is extremely heterogeneous and can be divided into two types: soil of a silty-clayey nature incorporating limy-marly elements (FROLDI & LUNARDI, 1994) and shaly-marly soil with a scaly and chaotic structure with intervals of thin limestone layers (FROLDI, LUNARDI, MANTOVANI & PODESTA', 1994).

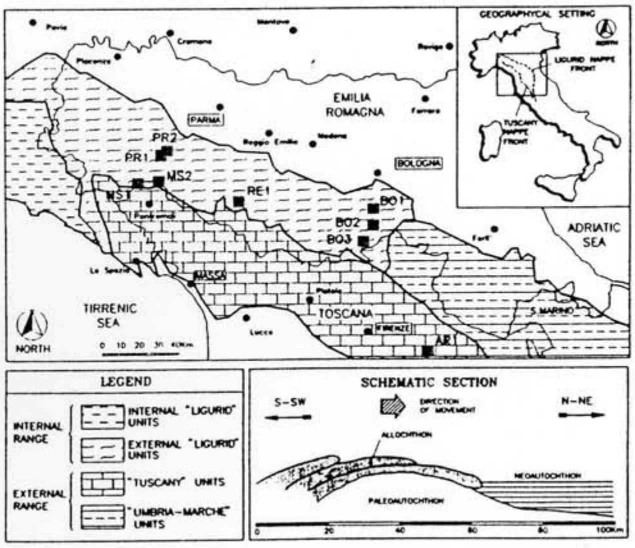

FIG. 1 - Geological setting

According to the "Classification of Complex Structural Formations" (ESU, 1977; AGI 1979) this ground can be classified as belonging to Group B - class B3 (Fig. 2).

The landslide phenomena studied all occurred on the Northern slopes of the Apennine chain with the exception of one single case (AR2) located on the Southern slopes: they were given reference codes as shown in Fig. 1.

GROUP		CLASS	DESCRIPTION
A	▨	A1	BEDDED CLAY OR SHALE, OFTEN FISSILE, MORE OR LESS FISSURED AND/OR JOINTED
	▨	A2	COMPACT BODY OF CLAY OR SHALE "SCAGLIA"
B	▨	B1	REGULAR BEDDING SEQUENCE OF ROCK AND CLAY OR SHALE, MORE OR LESS FISSURED OR JOINTED
	▨	B2	CHAOTIC BEDDING BODY OF CRACKED ROCK AND CLAY OR SHALE, FROM FISSURED OR JOINTED TO VERY HIGHLY FRACTURED
	▨	B3	FRACTURED CLAY OR SHALE, WITH ROCK FRAGMENTS DUE TO HIGH AND REPEATED TECTONIC SHEAR STRESSES
C	▨	C	ROCK BLOCKS OR FRAGMENTS, MORE OR LESS WEATHERED, WITH CLAYEY-SILT MATRIX OF HETEROGENEOUS NATURE

FIG. 2 - Classification of soils (After Esu, 1977 and AGI, 1979).

3. GEOTECHNICAL PROPERTIES

The soils under study was examined by means of laboratory tests which showed a high level of heterogeneity especially from the point of view of strength parameters.

The laboratory procedures were employed to determine the following:
- physical properties;
- plasticity;
- strength properties.

The results of the laboratory investigations are summarised in Table 1.

The soils in which the phenomena MS1, MS2, RE1 and BO2 occurred presented density and shear strength properties greater than in the other cases; this ground consisted of shaly- marly ground which, as observed on many occasions, outcrops predominantly on the ridge of the Apennines where the "External Ligurid Units" present a lower degree of allochthony and are therefore more compact.

4. LANDSLIDE CHARACTERISTICS

The movements that developed in the cases observed occurred on only slightly inclined slopes that consisted of soils of a clayey nature.

The areas affected by movements were identified in slopes that presented widespread and generalised surface disorder: they showed sizable deformations such as hump backs, reverse gradients and depressions.

The hydrographic surface pattern ob-

Table 1. Geotechnical properties.

LANDSLIDE	γ_s (KN/mc)	γ_n (KN/mc)	γ_d (KN/mc)	Sr (%)	Wn (%)	Wp (%)	Wl (%)	PI (%)	IC	Cp (MPa)	ϕ_P (°)	Cr (MPa)	ϕ_r (°)	TYPE OF TEST
PR1	27.8	20,8	16,8	85,7	17,9	19	45	26	1,04	0,017	16	0,002	10	DS-CD
PR2	\	19,9	\	71,8	15,6	20,1	45,1	25	1,18	0,016	17	0,002	10	DS-CD
MS1	\	21	\	\	12,3	16,4	28,9	12,5	1,3	0,145	25,4	0,005	16,5	DS-CD
MS2	\	20,8	\	\	11,5	17,3	30,8	13,5	1,6	0,04	23,3	0,03	21,7	DS-CD
RE1	27.6	23,6	21,6	\	9	15,9	28,7	12,8	1,5	0,006	29,9	0	23,8	DS-CD
BO1	\	20	\	\	20,4	23	56	33	1,08	0,03	15	\	\	TX-CU
BO2	\	21,9	\	\	10,5	18,8	35,7	16,9	1,49	0	23	\	\	TX-CU
BO3	\	21,5	\	\	13	18,3	32,2	13,9	1,38	0	13	\	\	TX-CU
						LEGEND								
γ	s=Specific Weight		Sr=Saturation		Wp=Plastic Limit			Cp=Peak Cohesion				DS=Direct Shear		
γ	n=Bulk Density		Wn=Natural water		Wl=Liquid Limit			Φ	p=Peak Friction Angle			TX=Triaxial Test		
γ	d=Dry Density				PI=Plastic index			Cr=Residual Cohesion				CD=Consolidated Drained		
					IC=Consistency index			Φ	r=Residual Friction Angle			CU=Consolidated undrained		
					IC=(Wl-Wn)/PI									

served was irregular and affected by deformation phenomena in progress.

Generally, the primary causes of instability are erosion phenomena at the foot of slopes where these cross principal drainage lines.

The unstable areas are frequently lacking in woodland vegetation.

The longitudinal profiles of the cases examined are shown in Fig. 3 where the following is also shown:

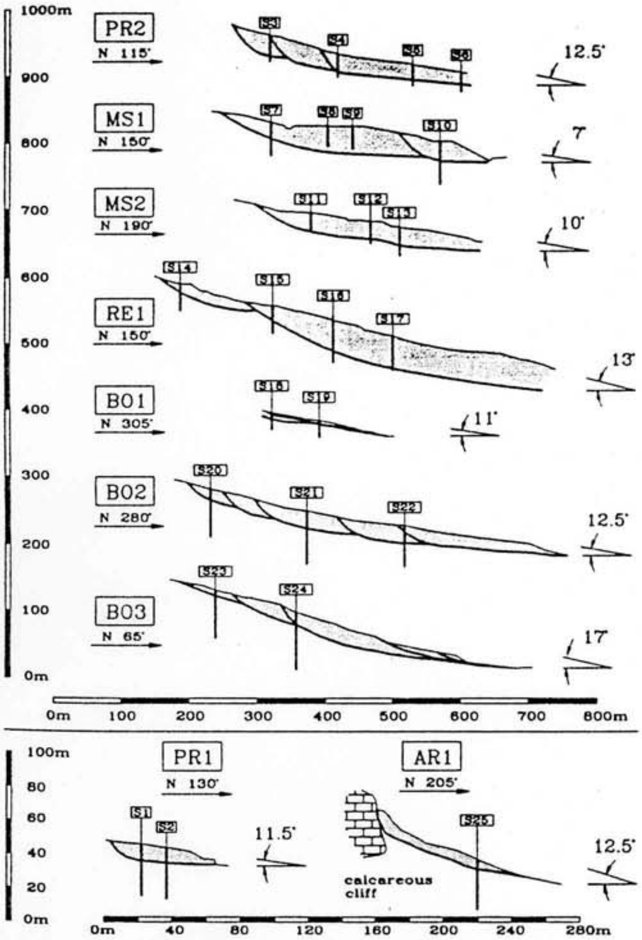

FIG. 3 - Landslide characteristics

- slip surfaces if present;
- masses in movement;
- bore-holes, inclinometer and deformations;
- direction of the cross section;
- average gradient of the slope.

The geometric parameters of the cross section of the landslide were recorded according to the UNESCO-WP/WLI report (UNESCO, 1990, 1993). As the entity of the dislocation in the landslides under study was often considerable it was not always possible to make precise reference to the measurements given in Fig. 4 (IAEG, 1990) and consequently the following was measured for each landslide:

- length;
- thickness;
- surface area;
- inclination of the slope.

The results of the measurements are given in Table 2.

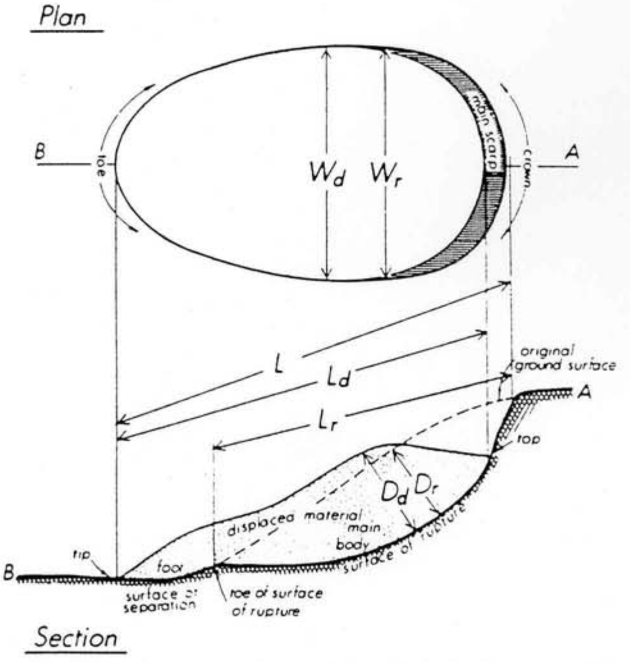

FIG. 4 - Geometric parameters from UNESCO report

Table 2. Geometrical features.

LANDSLIDE	Length (m)	Thickness (m)	Areal extension (m2)	Slope dip (°)
PR1	60	12	66000	11,50
PR2	400	25	129000	12,50
MS1	400	40	225000	7
MS2	450	30	\	10
RE1	300	12	35000	13
BO1	200	6	35000	11
BO2	560	25	80000	12,50
BO3	500	25	55000	17
AR1	200	8	30000	12,50

5. LANDSLIDE MONITORING

The landslides were monitored by means of the installation of inclinometer tubes in vertical borings that were deeper than the assumed slip surface. Subsequently the position of the lower side of the instruments was ascertained; these instruments were used to measure the absolute deformation along the vertical inclinometric axis.

The measurements were carried out using a removable inclinometric probe that was inserted in the boring along the whole of its length.

It is assumed that the functioning of the inclinometers is known to the reader.

An analysis was carried out on the readings from 38 No. inclinometers distributed as follows:

- PR1: 3 inclinometers;
- PR2: 6 inclinometers;
- MS1: 11 inclinometers;
- MS2: 2 inclinometers;
- RE1: 7 inclinometers;
- BO1: 2 inclinometers;
- BO2: 3 inclinometers;
- BO3: 2 inclinometers;
- AR1: 2 inclinometers.

The depth of the inclinometer tubes generally ranged between 30 and 40 meters but reaching a maximum of 70 meters at times (MS1, BO2).

The frequency of the readings was generally every two months but at times every month. Only in a few cases did the extreme slowness of the movement allow readings every 3-5 months (PR2, AR1).

Piezometric tubes were installed to monitor the excursion of the level of the water table. These however did not provide significant data on the existence of correlations between the level of the water table and the entity of movements.

It was impossible to obtain significant correlations because of both the insufficient number of measurements and the presence of different water tables under the slopes affected by movements. It was however noted that the level of the surface water table was generally contained within the first 10 metres from surface level.

In only one of the cases (PR2) affected by extremely slow deformations was topographical monitoring of the heads of the inclinometers carried out. It was done by measuring from an external base considered as fixed.

The importance of atmospheric precipitation with regard to movements was considered in only one case PR2, where data was available from meteorological stations very close to the zone under study.

6. DISCUSSION OF THE RESULTS OF THE MONITORING

6.1 General remarks

The large quantity of data obtained from the inclinometers made it possible to make important observations concerning the entity of displacements both in absolute terms and over time as a function of seasonal cycles and precipitation and also as a function of the geometrical characteristics of the phenomenon.

Some consideration was also given to the influence of orientation of the slope on rates of displacement.

In the case of PR2, topographical monitoring showed that soil deformation on the surface is due, above all the case of very slow creep movements, to temperature variation and precipitation that cause deformation of the topmost strata of the ground.

An analysis of inclinometric deformations identified different types of deformation in unstable masses depending on the failure mechanisms at work in the masses and on their distribution along the vertical length. Considerations of a general nature are made on this subject that may be useful for future classification of the phenomena according to velocity and deformation mechanisms.

6.2 Displacement and rate of displacement

The data on displacement that was processed relates to absolute deformation of the top end of the tube (down to a depth of one metre).

As a whole, this data was collected over a period beginning in October 1987 and ending in September 1993 (6 years).

The longest single period of observation relating to different phenomena covered a period of 19 months (BO1, BO2, BO3).

Figure 5 shows the absolute displacements of the different landslides; absolute displacement observed during the monitoring period generally falls within the 10-60 mm range. PR1 represents a different case which, with its 120 mm of

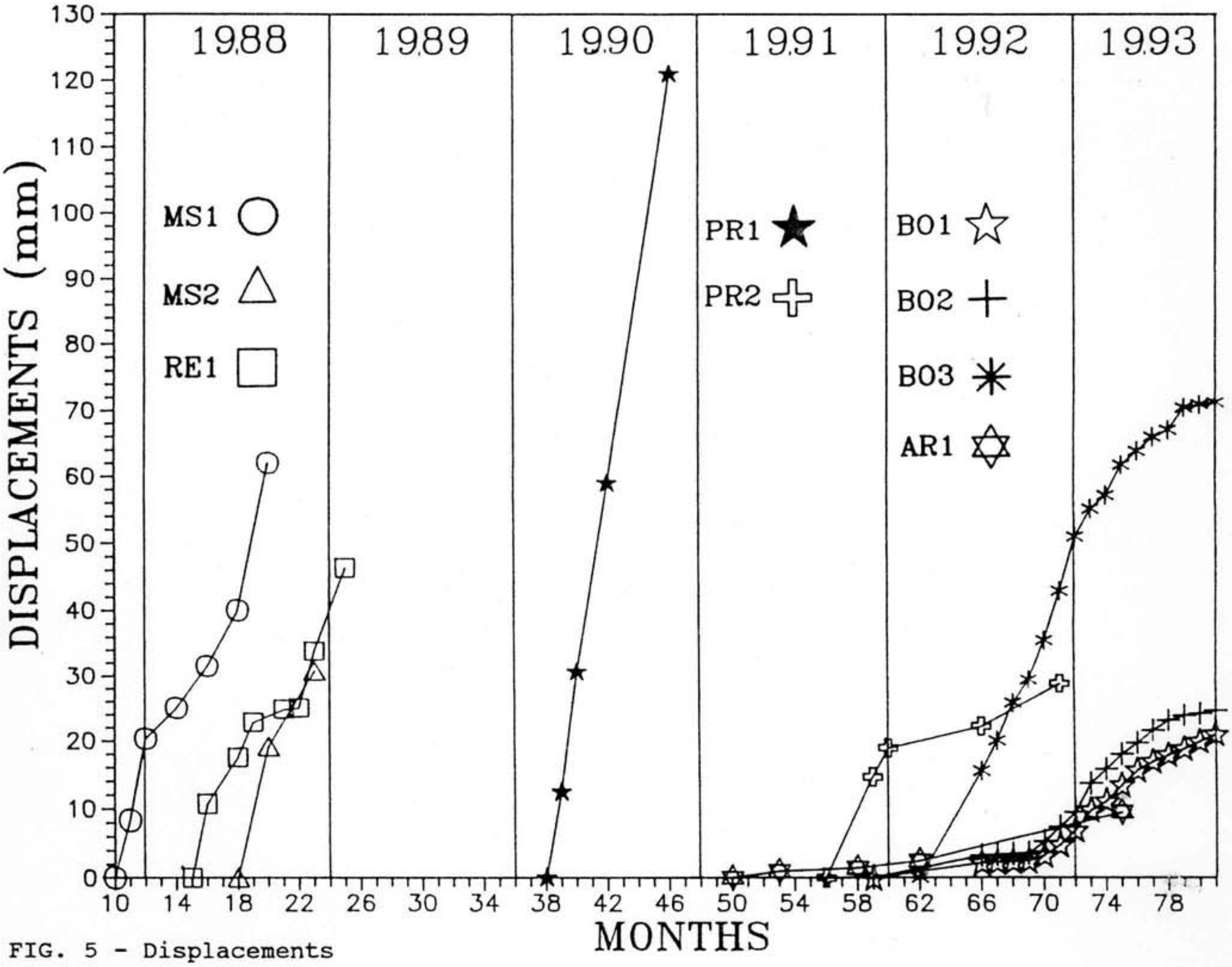

FIG. 5 - Displacements

displacement, caused the obstruction of the inclinometer tubes. Despite the small size of the deformation observed, the phenomena in question caused appreciable lesions in retaining and transport structures (walls, roads, viaducts, etc.) and buildings (houses).

Figure 6 shows the monthly rate of displacement allowing a comparison of the various cases studied; they are generally contained within the 2-12 mm/month range. PR1 represents an exception with a rate of 13 - 18 mm/month.

The graph in Fig. 7 was constructed to show rate of deformation on a seasonal basis.

All the values have been related to one hypothetical reference year. The graph shows, month by month, the average value and the standard deviation.

The following can be noted from the graph:

- the wide distribution of the values, above all winter and summer seasons (due to differences in the seasonal cycles for the years in which measurements were taken);
- an absolute peak in winter (December) equal to 4.5 - 8 mm/month;
- a relative peak in spring (March) equal to 2.5 - 3.5 mm/month;
- an absolute minimum in summer (August) equal to 0.5 - 2 mm/month;
- a relative minimum in winter (February) equal to 1.8 - 2.2 mm/month.

It was noted that there was a correlation between the geometry of a mass that was sliding and the rate of displacement (Fig. 8): the relationship between the length and the thickness (ratio length/thickness) of a sliding mass decreased as the velocity of the deformation increased. The physical meaning of this observation can be summed up in the fact that given the same length, deeper landslides are faster. They tend to develop multiple approximately circular imbricate surfaces and the coalescence of these constitutes the landslide as a whole. Landslides of limited surface area with a low length to thickness ratio (thick) generally possess a single well defined failure surface that is of the approximately circular or polygonal type.

On the other hand, landslides with a high length to thickness ratio (thin)

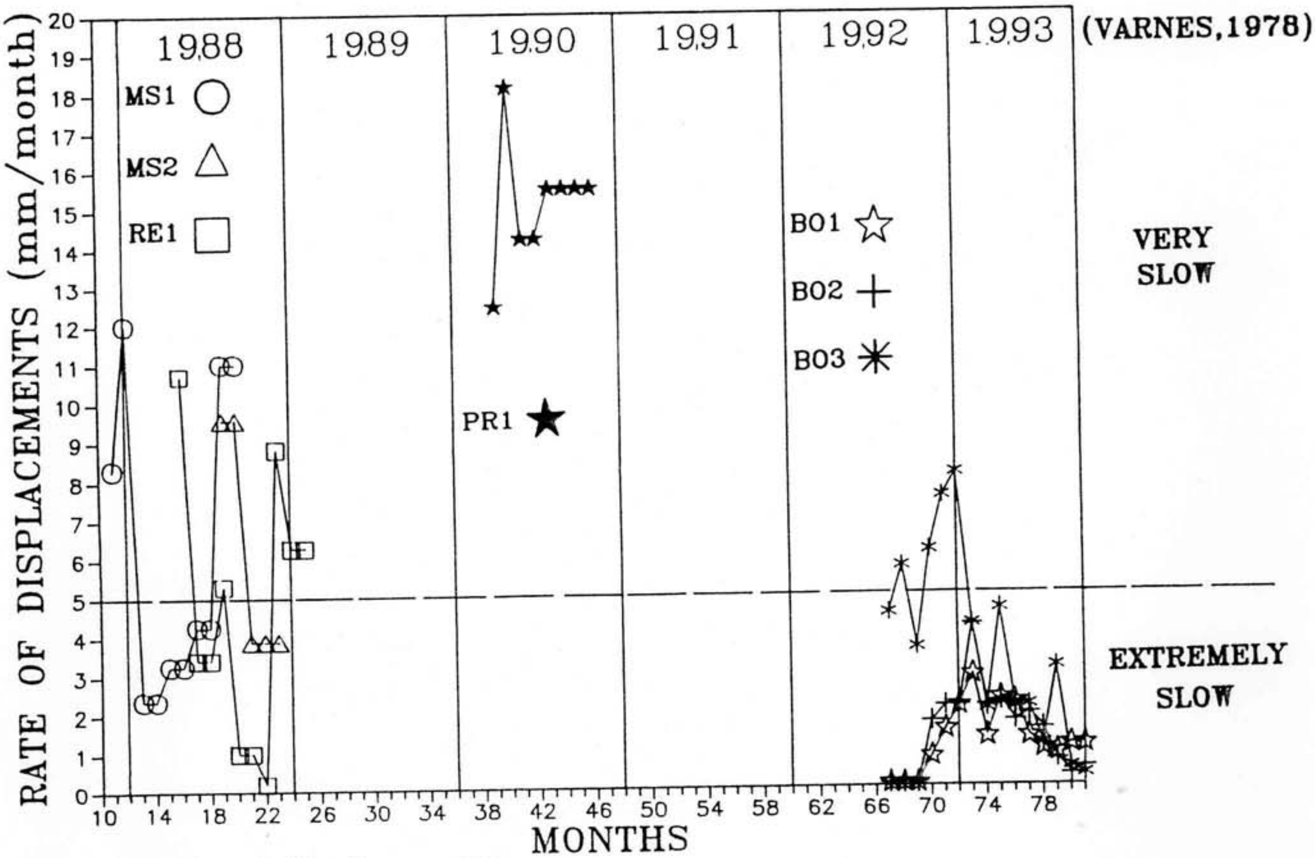

FIG. 6 - Rate of displacements

move according to creep mechanisms at very slow velocity and do not have well defined slip surfaces.

Furthermore, the rate of displacement seems to depend on the orientation of the slope (Fig. 9). Slopes facing South show higher rates of displacement as is normally observed with erosion processes.

According to the classifications in general use (SKEMPTON, 1953; CROZIER, 1973; SELBY, 1976; EAST, 1978) gravitational slope movements can be divided into three classes on the basis of the percentage ratio between thickness and length (T/L):

- FLOWS T/L = 0.5 ÷ 3%
- SLIDES T/L = 5 ÷ 10%
- SLUMPS T/L = 15 ÷ 30%.

On the base of this classification the cases observed can be grouped in:

- FLOWS: BO1 (3%), AR1(4%)
- SLIDES: BO3 (5%), RE1(4%), BO2 (4.5%), PR2 (6%), MS2(6%), MS1(10%)
- SLUMPS: PR1 (20%).

Some authors (JAHNS, 1978; CROZIER, 1973, 1986) provide a qualitative description of the geometry of the instability mechanisms and the rates of displacement. Most flows are described as moving as a viscous mass with intergranular movements predominating with respect to shear movements along a surface. They are characterised by a shear surface that is poorly defined and parallel to the topographical surface. They are classified as creep when, according to the Varnes classification (VARNES, 1978), they are extremely slow (Rate of displacement < 5 mm/month).

In this case creep can be understood as the movement of an almost viscous flow that occurs under shear stress sufficient to produce permanent deformation which, however, is too weak to generate surface failure (RAHN, 1986). Generally the length is much greater than the thickness to the point where they become "Creep mantles" (VARNES, 1978).

The inclinometer deformations that

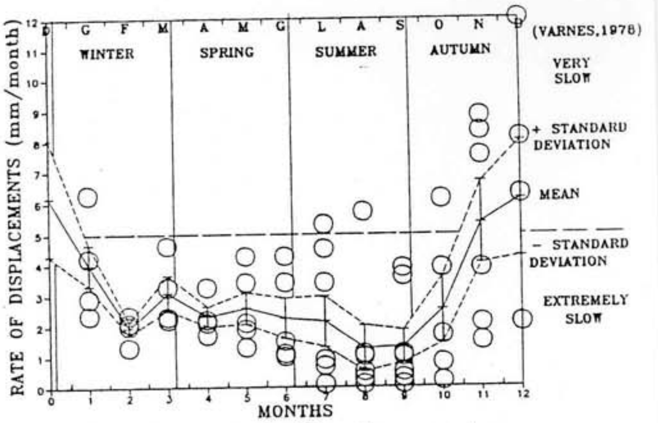

FIG. 7 - Seasonal displacements

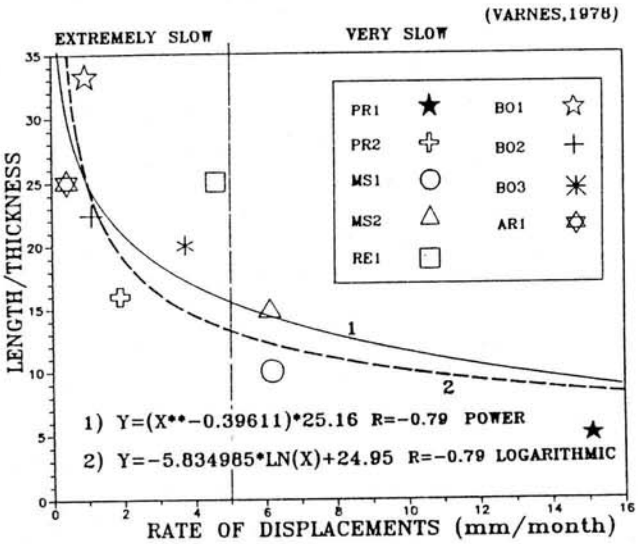

FIG. 8 - Geometry and rate of displacement

result in these cases are shown in Fig. 10a.

The slides are characterised by one or more levels of slip practically parallel to the topographical surface. They are essentially traslational movements. A typical inclinometric deformation is shown in Fig. 10b: it generally has a well defined multiple shear surface which is imbricate at times.

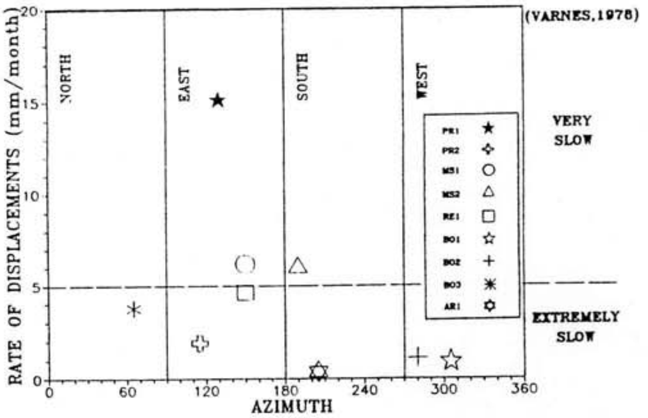

FIG. 9 - Orientation and rate of displacements

Slumps or rotational slides are generally characterised by curvilinear concave shear surfaces facing upwards. The mass remains more or less intact or separated, generally into a small number of solid blocks, by distinct near vertical cracks. The thickness is rather large with respect to the length.

Slumps rarely occur on natural slopes while they are one of the more common types of failure where there is excavation at the foot of slopes.

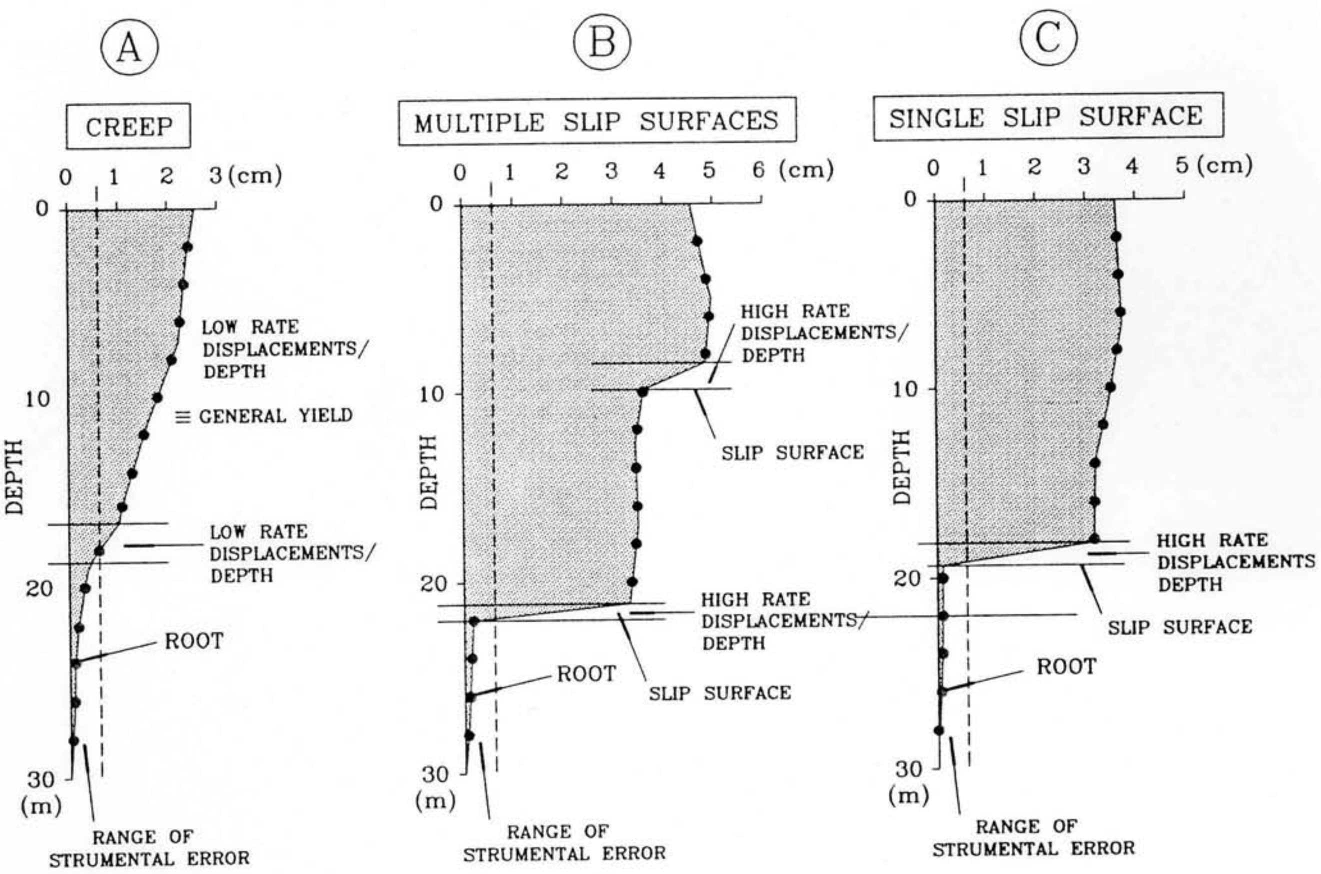

FIG. 10 - Type of inclinometric deformations

Typical inclinometer deformations show a single well defined slip surface where the displacement to depth ratio is decidedly high, at least in one point (slip surface) (Fig. 10c).

The rates of displacement observed in the cases under study do not correspond to those provided by the above mentioned classification (JAHNS, 1978), but are decidedly lower.

The Varnes classification was used to group together the following cases:

- very slow = 5-125 mm/month: PR1, MS1, MS2;
- extremely slow = < 5 mm/month: PR2, RE1, BO1, BO2, BO3, AR1.

The influence of precipitation on displacements relative to the heads of the inclinometers was verified on only one occasion (PR2); a relative displacement is intended as an absolute deformation that a point is subjected to if the position of the previous reading is taken as a zero reference point.

This concept expresses deformation of the soil that need not necessarily be directly connected to the movement of the landslide but which may be due, in some cases, to contraction and expansion of the ground at the surface caused by drying up of and soaking in rain water.

This type of deformation was recorded by means of inclinometric and topographical measurements taken from the head of the inclinometer. The values considered for precipitation were the averages over a period of twenty years.

The graph in Fig. 11 shows a certain spread of the data due to the singularity of the extremely slow movement; in fact the ground in proximity of the topographical surface is very sensitive to all climatic agents including variations in temperature. The only appreciable correlation found was the deformation response of the ground to autumn rains.

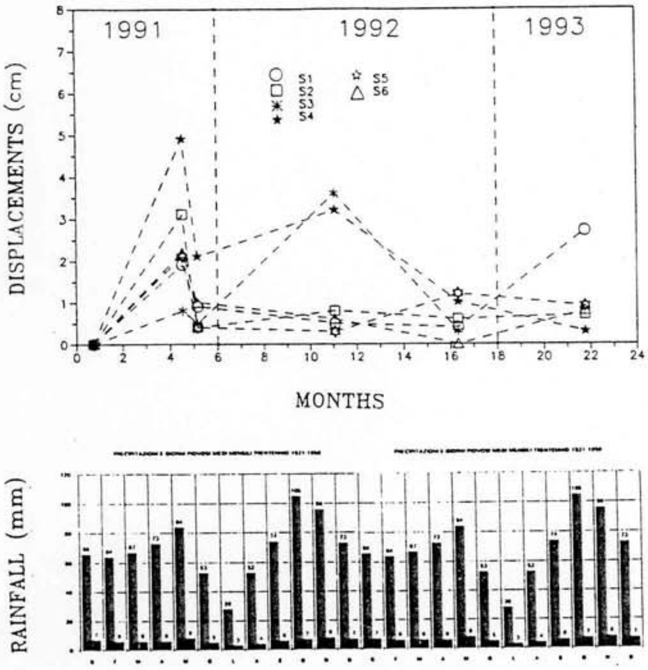

FIG. 11 - Displacements and rainfall

7. CONCLUSIONS

Nine gravitational phenomena were analysed. These were of varying extension and geometry and were located in the "Scaly Clays" of the Northern Italian Apennines. The principal geotechnical characteristics of the soils was examined and this could be divided into two categories: one of a clayey nature and one of a shaly-marly nature.

Inclinometer measurements taken over an adequate period of time were used to analyse, for each phenomena, absolute displacements and rates of displacement with respect to seasonal cycles, geographical orientation and the geometry of the body of the landslide.

It was found that most of these phenomena are of a very slow or extremely slow nature (VARNES, 1978); the greatest velocities were recorded in autumn and spring and on slopes facing South. Greater velocities were measured for masses with a low length to thickness ratio in agreement with the findings of other researchers (JAHNS, 1978; CROZIER, 1973).

An analysis of the pattern of inclinometric deformation made it possible to classify movements as a function of failure mechanisms acting inside the mass, again in agreement with the findings of the above mentioned researchers.

Finally, with one case only, it was found that, with extremely slow movements, deformations of the uppermost strata of the soil not caused directly by the general movement of the landslide may be important (causes: retaining of water and heat).

The authors feel that the study presented here may be considered as a valid source of reference for future studies related to land management and planning.

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