Some effects on natural slope stability induced by the 1980 Italian earthquake*

Conséquences du seisme de l'Irpinia de 1980 sur la stabilité des talus naturels

B. D'ELIA, Professor of Geotechnical Eng., University of Roma, Italy
F. ESU, Professor of Geotechnical Eng., University of Roma, Italy
A. PELLEGRINO, Professor of Geotechnical Eng., University of Naples, Italy
T. S. PESCATORE, Professor of Geology, University of Naples, Italy

SYNOPSIS. On November 23rd, 1980, a strong earthquake in Irpinia triggered numerous landslides and deformational phenomena in natural slopes composed of rocks, clays or structurally complex formations such as are widespread along the Apennine chain. With the exception of rock falls, the movements involved large ancient, slide bodies and because they have a low margin of safety these formations are periodically mobilized by the earthquakes that successively affect the area. This paper deals with three typical cases, concerning two large landslides and the deformation of a hill, wich involve stiff overconsolidated clays or structurally complex formations where clay is the predominant component. The main features of the movements and the results of geotechnical surveys and direct surface observations emphasize the complexity of the phenomena which can be only explained on the basis of hypotheses concerning the stress fields and their evolution in time.

INTRODUCTION

Earthquakes are known to be a triggering cause of landslides. In clayey or detrital soils, where liquefaction must be totally ruled out, the failure mechanisms causing the landslides are far from being understood.
The phenomena observed for these soils vary widely both in terms of type and magnitude of ground movements.
The literature is rather poor in papers dealing with earthquake induced slides in clayey soils; for Italy, some historical data are available on slope movements in clayey soils (Cotecchia et al.,1969). However during this century, even though very severe earthquakes have occurred (Messina, 1908; Avezzano, 1915; Irpinia, 1930 and 1962) landslides in clay slopes have neither been detected nor studied.
On November 23rd, 1980, the earthquake in Irpinia triggered off numerous landslides and deformation phenomena in natural slopes formed of clays or structurally complex soils where clay is the predominating component.
Given the general lack of knowledge of such phenomena, in the framework of the effects induced by the 1980 earthquake, three typical cases were selected as a pilot study: two large landslides and the deformation of a hill consisting of varicoloured clays, covered by a thick conglomerate slab.
The study approach focused mainly on surveys and direct surface observations. Though there are some uncertainties due to the lack of data on the situation prior to the earthquake, this study does give some indications for explaining the complex processes triggered inside natural slopes by seismic actions.

GEOLOGICAL SETTING AND SEISMICITY OF THE AREA

The earthquake of the 23rd November, 1980, ($M = 6.5$) with intensity VI-X MSK scale involved a broad stretch of the Southern Apennines, over a 100 km long in the NW-SE direction and about 50-60 km wide in the SW-NE direction; this is a high seismic risk area where earthquakes having intensity X-XI degrees have occurred frequently over the last 500 years (1456, 1688, 1694, 1702, 1732, 1930). The main shock of the 1980 earthquake lasted about 50 s for accelerations > 0.05 g, and about 80 s for accelerations > 0.01 g, and was followed by numerous aftershocks.
A simplified sketch of the geolithologic and tectonic characteristics of the region is shown in Fig. 1.
The southern Apennine consists of three main zones in succession from W to E :

- The Apennine Chain is formed of various "nappes" with highly differentiated lithostratigraphic composition. The main geological units (Mesozoic-Cenozoic) consist of monotonous sequences of carbonatic rocks, 4000-5000 m in thickness, and of sequences of "structurally complex formations", over 1000 m thick. The tectonic events that occurred inside these allochthonous units induced very high fracturing in the rocks and minute flaking in the clays. To the north-west of the chain there are areas of tectonic sinking, where volcanic apparatuses developed.
- The Bradano Foredeep is filled by terrigenous sequences (Plio-Pleistocene) where clayey and clayey-sandy soils prevail. These are authoctonous

* The research has also seen the participation of: S.Di Nocera, G.Iaccarino, F.Rippa for the geological aspects; I.Cotti, G.Federico, G.Fenelli, M.Paparo Filomarino, L.Picarelli, G.Tancredi for the geotechnical aspects; G. La Barbera, C. Nuti for the dynamic aspects.

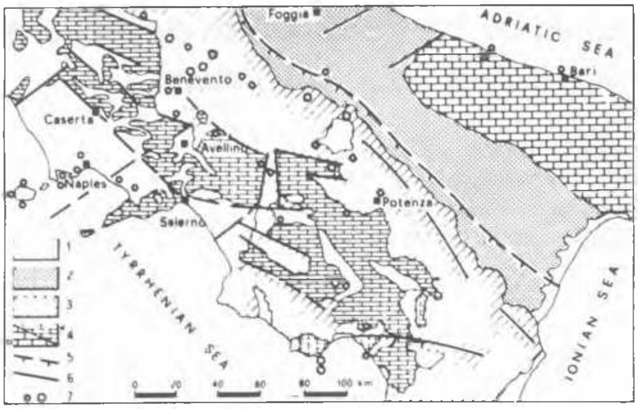

Fig.1 Geolithologic scheme of southern Italy.
1. Volcanic and sedimentary deposits (Quaternary);
2. Plio-Pleistocenic deposits of the Bradano Foredeep;
3. Terrigenous deposits of the Apennine Chain (Structurally complex formations);
4. Carbonatic rocks of the Apennine Chain (a) and of the Apulian Foreland (b) (3 and 4: Mesozoic and Cenozoic);
5. Eastern boundary of the allocthonous units;
6. Main Plio-Pleistocenic faults;
7. Epicentres of major earthquakes.

soils that were involved only in tectonic upheaval movements.

- The Apulian Foreland is the most stable area in the Southern Apennine and it consists of a carbonatic rock sequences (Meso-Cenozoic), some 5000 m thick; these sequences are practically underformed.

The mostseismically active zone is the Apennine Chain,that over the last two million years underwent phases of intense upheaval at a rate of 1-1.5 mm/year. Such upheaval occurred through two main sets of faults having a NW-SE and NE-SW trend.
Besides the lithological characteristics, the sliding proneness of hill-slopes is due also to the structures induced by the tectonic events.
A determining event in controlling slope stability was the Wurmian glacial phase that reached its peak 18,000 years ago, and that depressed the sea level down to 100 m below the present level, thus bringing about a deepening of the main talwegs and instability conditions of the slopes.
The slides alternated periods of quiescence and periods of regional and local mobilization.

GEOTECHNICAL CHARACTERISTICS OF THE EPICENTRAL AREA

The larger slides involve slopes consisting of the Plio-Pleistocenic terrigenous units of the Bradano Foredeep and of structurally complex formations of the Apennine Chain.
The Plio-Pleistocenic soils are essentially represented by highly overconsolidated marine clays with a high $CaCO_3$ content ("blue clays") and by conglomerates. The blue clays are characterized by synsedimentary discontinuities and by joints that are generally closed. The conglomerates are composed of round-shaped gravels and silty sands. Due to variations in degree of cementation their mechanical properties range from those of soft rocks to those of incoherent deposits.
The structurally complex formations are classed as follows (AGI, 1979):

- arenaceous-pelitic and calcareous-pelitic formations;the structure, orderly in some places and disarranged in others, is formed of alternating layers of weak to hard rock and highly indurated clay;the lapideous component is always fractured; the clayey component has a typical scaly or fragmented structure;
- mainly pelitic formations with a typical scaly structure, with a small amount of rock fragments (limestones, sandstones, marls).

The mechanical behaviour of such formations depends on their macrostructural features, on the rock-clay ratio, and on the mechanical characteristics of the pelitic component.
The clayey fractions of the two lithologic types, having different composition and structure have some common properties(Pellegrino and Picarelli, 1984): a high consistency depending on high preconsolidation loads and diagenetic bonds; the presence of a closely-spaced network of discontinuities bounding fragments ranging from a millimeter to a few centimeters; a marked physical and mechanical weakness depending on the structure and index properties.

LANDSLIDES AND GROUND DEFORMATION PHENOMENA TRIGGERED BY THE 1980 EARTHQUAKE

The earthquake triggered numerous huge flows, slides and complex slides (largest volume > 10×10^6 m^3) in natural slopes, and ground deformation phenomena. Rock falls were uncommon and of limited extent (Fig.2 and Table I).
Most of the mobilized slides were old, dormant or active slides. In most cases, there was some delay (a few hours to a few days) between the main shock and the slidings(Cotecchia, 1982; D'Elia,1983). Some of these slides had been set in motion also by the 1930 earthquake.
Amongst the many slides that have occurred, two that are quite similar in terms of their geometry and kinematics have been studied; they are also quite characteristic and representative of the earthquake induced instability phenomena.
A hill, on top of which rises an ancient small town (Bisaccia), was chosen to study the deformation processes. This case, because of the hill shape and subsoil profile, represents a situation that is rather common throughout central and southern Italy where many old towns were built on hilltops. The practical and scientific interest of this case lies in the fact that the differential ground displacements of the hill have influenced the type and distribution of the damages affecting the buildings.

TABLE I - Main landslides triggered by the Nov. 23, 1980 earthquake

TYPE OF MOVEMENT	LOCALITY	LITHOLOGY	SURFACE AREA (Km^2)	SEISMIC INTENSITY (MSK)	DELAY OF EVIDENT MOVEMENTS WITH RESPECT TO THE MAIN SHOCK		
					NIL	FEW HOURS	FEW DAYS
FALL	VALVA	Limestones	--	IX	X		
	RAIA Mountain	"	--	IX	X		
	COLLIANO	"	--	IX	X		
	BALVANO	Limestones and dolomites	--	VII	X		
SLIDE	S.GIORGIO LA MOLARA I	Sandstones and clays	3,0	VI			X
	SAURO Stream	Clays and varicoloured clays	1,9	VI			X
	ANDRETTA	Clays and conglomerates	0,8	VIII		X	
	TORELLA DEI LOMBARDI	Sandstones,marly clays and calcarenites	0,5	VIII			X
	CALITRI	Clays and varicoloured clays	0,3	VIII		X	
	S.GIORGIO LA MOLARA II	Calcarenites and clays	0,3	VI		X	
	S.ANGELO DEI LOMBARDI	Clays and conglomerates	0,3	X		X	
	CAPOSELE	Sandstones	0,08	IX			
	S. FELE	Clays and marls	?	VII		x	
FLOW	SENERCHIA	Debris and varicoloured clays	1,0	VIII-IX		X	
	BUONINVENTRE	Marls and clays	0,9	IX		X	
	CALITRI	Clays and varicoloured clays	0,2	VIII			X

LANDSLIDES

Description

The two slides occurred in slopes which were affected by slides in past times. The profile of the slopes before the quake was marked by benches at different heights and sheer scarps, showing a typical slide morphology. The geometry of the slides is given in Table II.
The first slide (Torella dei Lombardi) occurred on a slope consisting of structurally complex soils of the Apennine Chain. An outline of the local geology is given in Fig. 3. The bedrock consists of stratified calcarenites with few and thin layers of more or less hardened and foliated marly clays. The calcarenites are followed by sheared argillites having a chaotic structure, followed by a weakly cemented sandstone with interbedded clays. A chaotic melange of these components forms the body of the slide.
The geological units are crossed by vertical faults that have lowered the bedrock surface towards NW.

TABLE II - Geometrical characteristics of the studied landslides

LANDSLIDE	ELEVATION m a.s.l.	EXPOSURE	LENGTH m	WIDTH m	AVERAGE SLOPE INCLINATION	ESTIMATED VOLUME m^3
TORELLA DEI LOMBARDI	460-660	N	1100	300-400	8.5°	20×10^6
ANDRETTA	560-760	WNW	1300	400-750	7.5°	30×10^6

Fig. 2 Isoseismals (MSK scale) of the November 23rd 1980 earthquake and distribution of landslides

So far, it has been possible to collect undisturbed surface samples of the argillitic component in the slide body. The laboratory test results are shown in Table III.
Small springs in the upper part of the slide show that the water table is rather shallow.
The slope movements evolved very slowly in the days following the earthquake, through a succession of slides, falls and flows. During the 24 hours immediately after the main shock, slight fractures were noticed on the surface of a road across the upper part of the slide.
Large displacements occurred in the following 48-72 hours causing the opening of fractures on the ground surface

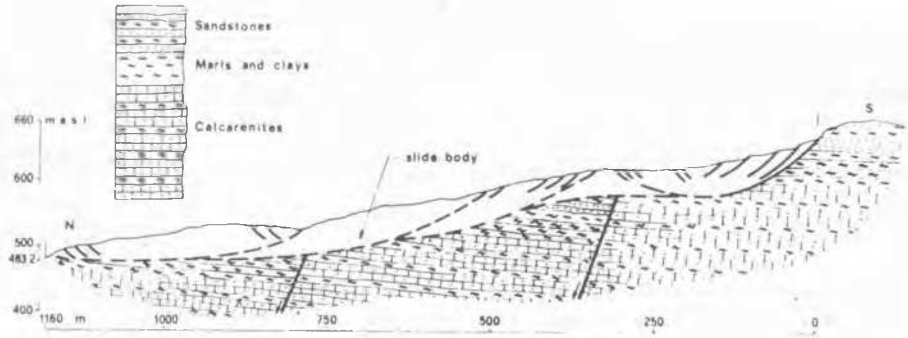

Fig. 3 Torella landslide

and the sinking of some parts of the slope. The slide toe dammed a small river 10 days after the quake.
The slide does not appear to have markedly changed the topography of the area. Horizontal displacements range between 20 and 30 m and the vertical displacements are of the order of a few metres. Small ponds developed in depressed parts of the slope and the gullies beds were diverted.
The second slide(Andretta) involves a slope consisting of Plio-Pleistocenic soils (Fig.4). The upper part of the slope consists of conglomerates, a few tens of metres thick, overlying a sequence of sandy and silty clay layers having an overall thickness of about 40-50 m; the lower middle part consists of sandy and silty layers and a few conglomerate beds. The conglomerates are poorly cemented and almost totally lack cohesion; the clays are slightly cemented and overconsolidated. The geotechnical properties of the clays obtained in the laboratory on undisturbed samples taken from shallow trenches in the upper zone of the slide are given in Table III.
According to historical data, the slope seems to have been affected by slides also a few centuries ago after a strong earthquake (1694 ?). The middle and upper parts of the slope had in any case remained quite stable over the last 200 years.

TABLE III - Main geotechnical properties of the clays forming the landslide bodies (average values)

	γ (kN/m^3)	w_n (%)	w_L	I_p	CF (%)	S_E (%)	SHEAR STRENGTH (*)			
							c'_P (KPa)	φ'_P	c'_R (kPa)	φ'_R
1	20.1	26.4	55	20	21	100	28	13.5°(') 19.1°(")	--	--
2a	20.0	17.6	38	17	38	80	25	27°	10	13°-15°
2b	21.8	14.6	42	20	45	90	--	--	--	--

(*) Tests on soaked specimens (shear) and on specimens subjected to back-pressure (triaxial)
(') Triaxial compression tests
(") Direct shear tests
1. Torella
2a. Andretta - Softened clays
2b. Andretta - Fresh clays

The movements induced by the 1980 earthquake were evident at twelve hours from the shock and they developed over the ensuing twenty days. On the whole the slide did not modify the general profile of the slope: some pre-existing scarps broadened and others were newly formed reaching a maximum height of 15 m; the crown of the slide withdrew by about 50 m; maximum horizontal movements at the foot are 20-30 m. The slide started at the foot and gradually propagated uphill. The slide area can be divided into four zones (I-IV, Fig.4), where the movements occurred in succession at different times. After twelve hours from the first shock in zone I scarps and cracks about 1 m wide were formed;in zone II, the cracks were a few centimetres wide, and in zone IV there were only slight cracks on the ground surface. Three days later the slide was fully developed; the movements continued for three weeks, ending when the river at the slope toe was dammed.
According to the water levels in some wells prior to the earthquake the water table was almost at ground level. After the movement in the middle and upper parts of the slope the water levels dropped by a few metres.
The landslide consists of multiple rotational slides, of the retrogressive type, along pre-existing slip surfaces. Near the slope edge, new failure surfaces have been formed thus making the crown retreat. The set of single rotational slides may be represented as a translational slide of the whole slope along an envelope surface which is almost parallel to the surface of the slope.

Interpretation

The two slides are quite similar from the geometric and kinematic points of view even if the structural and lithological characteristics of the soils involved are different.
For lack of direct evidence, it cannot be stated whether the Torella slide started at its foot and then propagated uphill, or whether it started uphill. Given the heterogeneity and the complexity of the soils forming the body of the slide, no stability analyses have been carried out on the basis of the results of the tests conducted on the surface samples.
The greater homogeneity of the soils of the Andretta slide make it possible to interpret the mechanism of the process even though some elements have not been totally assessed.

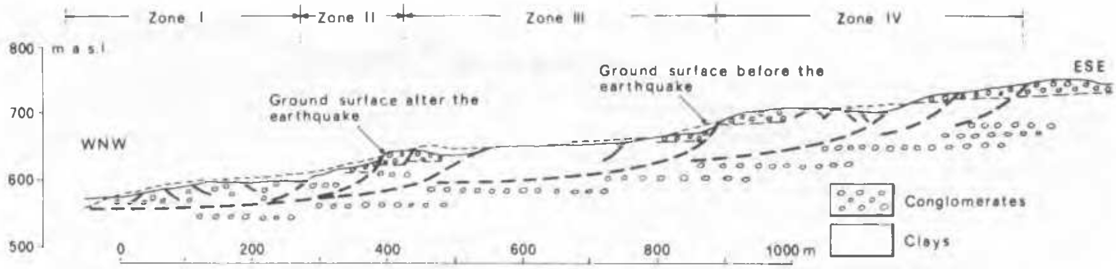

Fig. 4 Andretta landslide

Keeping account of the average dip of slope and of the depth of the water table, and by ascribing the parameters of residual shear strength of the clays measured in the laboratory (c'_R = 10 kPa and φ_R = 13°-15°) to the shear strength along the pre-existing failure surfaces, the overall stability conditions of the slope before the earthquake appear to be very close to limit equilibrium conditions.

A stability analysis shows that the safety factor of the lower part of the slope (zone I) in static conditions is just over 1 (1.1-1.2). Thus, in order to set this area moving, small dynamic actions (in terms of horizontal equivalent static forces) or slight increments of pore water pressure are sufficient (seismic coefficient k = 0.02 or Δu = 10-15%).

In zone IV, along the edge of the slope where first-time slides occurred, inertia forces or increases in pore water pressure, even if very intense, are not sufficient to account for failure. It is necessary to consider the changes in the boundary conditions brought about by the large displacements downhill in zones II and III.

As a conclusion, the results of the analysis are in agreement with the retrogressive nature and with the evolution in time of the Andretta slide.

GROUND DEFORMATIONS

A ground deformation process that has not caused slides was studied. The hill on top of which the old, small town of Bisaccia rises was chosen for this purpose (Figs.5 and 6). The hill consists of a large Plio-Pleistocenic continental conglomerate slab having a thickness of some fifty metres, overlying a very thick varicoloured clay formation; the large conglomerate slab forms a flattopped spur extending from S to N, interrupted by a fault that lowers the whole area, where the most ancient portion of Bisaccia is built, by about 20-40 m. Fractures, probably of tectonic origin, divide the slab into rather regular blocks whose sides measure up to 100-200 m.

The conglomerates consist mainly of gravel and blocks (d_{max} = 0.5 m) of poligenic origin and with rounded edges; to a lesser extent there is also a silty sandy fraction that provides some cementing.

The highly tectonized varicoloured clays have a typical scaly structure, the single scales being a few mm in size; the clays are moreover crossed by closely-spaced discontinuities (cm, dm) generally planar, polished and rarely slickensided.

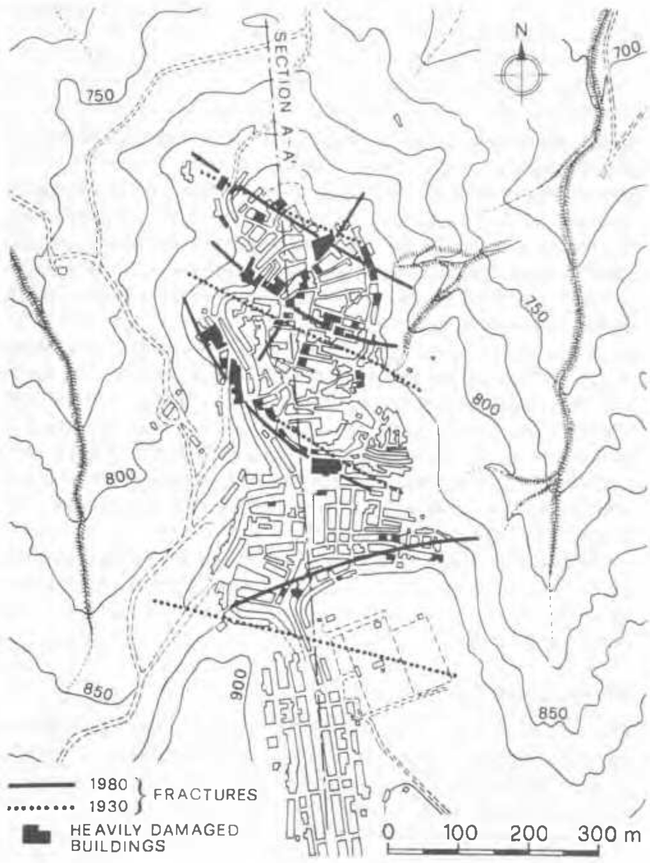

Fig. 5 Plan of the Bisaccia Hill. Main ground fractures along which buildings were severely damaged during the 1930 and 1980 earthquakes

Even though data from direct investigations are not available, the observations made so far, justify the assumption that in this area there are two hydraulic situations: i) zones where the ground water table corresponds to the upper surface of the varicoloured clays (valley beds or below the conglomerate slab); ii) zones where the ground water table is decidedly below the ground surface.

The laboratory results on samples from a site to the W of the town are shown in Table IV and in Figs. 7, 8 and 9. High plasticity and consistency values and a strong tenden-

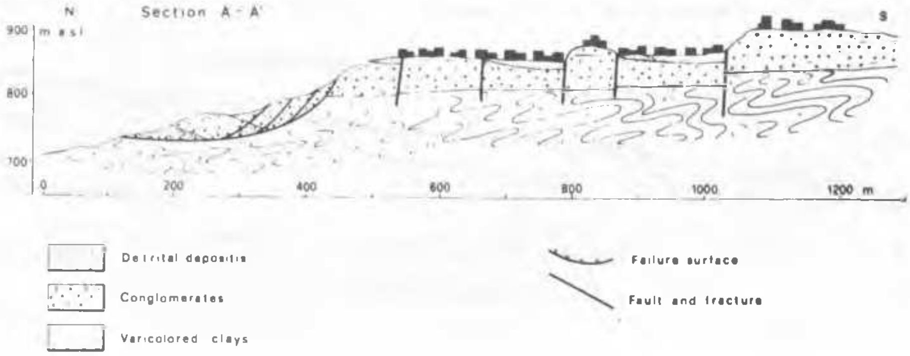

Fig. 6 Schematic geological section of the Bisaccia Hill

cy to swell are found in agreement with the degree of overconsolidation (σ_p = 1-1.2 MPa).
The triaxial and direct shear tests point out a marked influence of the capillary stress and of the structure (Fig. 7). Keeping account of the consistency, the low strength (due to the structure and the high plasticity) agrees with the current knowledge of this type of materials (Pellegrino and Picarelli, 1984).
Some cyclic triaxial tests were also performed on isotropically and anisotropically consolidated specimens by applying the load through a series of 25 cycles up to failure. These tests gave higher strength than the static tests. However, it is to be noticed that the number of cycles was not very high. Resonant column tests show a reduction in the normalized shear modulus which is lower than that obtained for other clays (Fig.9).
In the small town of Bisaccia two types of ground movements occurred: slides along the boundary of the conglomerate spur and relative displacements along the fractures in the conglomerate slab.

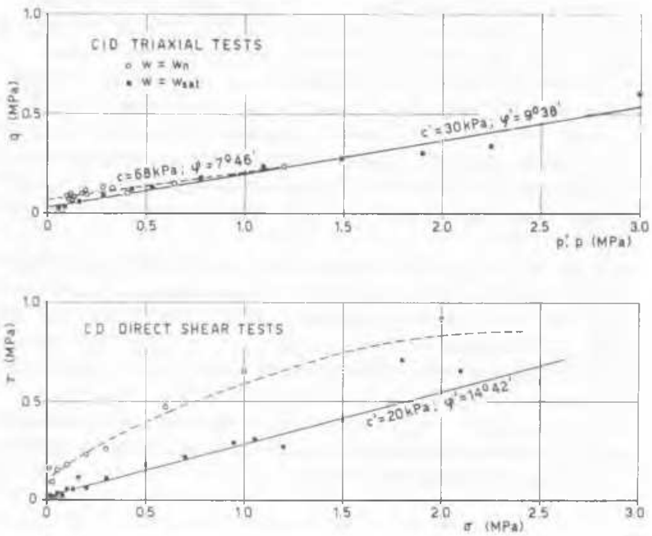

Fig. 7 Bisaccia clays. Influence of saturation degree on strength.

$W = W_n$: natural water content ($W_n < W_{sat}$)

$W = W_{sat}$: soaked specimens (direct shear tests) or tested under back pressure (triaxial tests)

Slides along the spur border.

The varicoloured clays on the hill slopes are undergoing intense erosion; such processes cause many slides, mostly of the rotational type which involve large conglomerate blocks and some small wedges of clay at the slab foot. Such slides were active even in ancient times, independently of the earthquakes, and they produce a gradual retreating of the edges of the slab.

TABLE IV - Bisaccia: Main index and compressibility properties of the varicoloured clays

γ KN/m^3	W_n (%)	W_L	I_p	CF (%)	S_r (%)	σ_s (MPa)	σ_c (MPa)	C_c	C_s (*)
20.7	21	128	88	68	97	0.4-0.6	1-1.2	0.22	0.19

(*) between 1 and 0.1 MPa

σ_s Swelling pressure

σ_p Precompression pressure

C_c Compression index

C_s Swelling index

These slides may be explained, with some approximation, by using the parameters inferred from the $W = W_{sat}$ tests, in that it is quite likely that where slides did occur the groundwater table coincided with the upper surface of the clays. The stability of high cliffs in the varicoloured clays to the W of Bisaccia is in agreement with the $W = W_n$ tests.
The overall stability of the Bisaccia Hill is governed by the mechanical properties of the varicoloured clays in depth that have not been measured at the present time.
If the strength parameters of the surface clay are assumed, it can be inferred that the safety margins of the whole hill are low also in the absence of dynamic actions and the stress level in the subsoil is high.

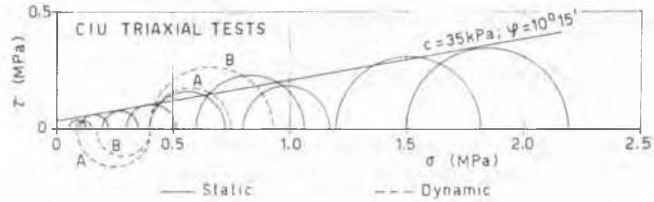

Fig. 8 Bisaccia clays. Undrained triaxial tests.

Specimen A : Isotropically consolidated
Specimen B : Anisotropically consolidated

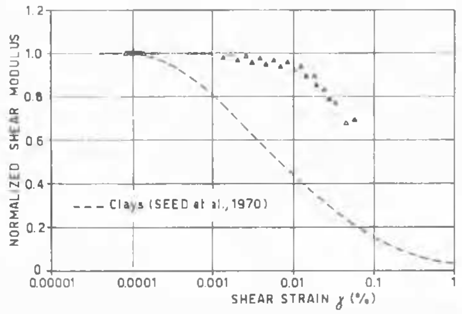

Fig. 9 Bisaccia clays. Dynamic shear modulus

Earth movements caused by the earthquake.

Damage to the buildings rising along the fractures of the conglomerate slab occur concurrently with the main shock of the earthquakes that periodically strike this region. Historical information confirms this. On the occasion of the 1930 and the 1980 earthquakes, great damage was caused to the buildings rising along the lines of fracture in Fig.5. Analyses of the damage to these buildings together with high precision levelling, repeatedly carried out in the town (University of Ancona), show that the seismic event induces permanent relative displacements of the blocks forming the conglomerate slab, with vertical and horizontal components of the order of a few centimetres up to a decimetre. The damage to the buildings is therefore to be related to these displacements rather than to the direct action of the shock.

The levellings show that the displacements rate of the blocks decreases in time, but the displacements are still somewhat active at one year from the earthquake. On the basis of the condition of the buildings it can be stated that there does not appear to be any movement along the fractures in the time interval between the earthquakes.

On the basis of these data it may be inferred that the blocks move because of deformations induced by the quake in the underlying clayey formation.

An analysis of the dynamic behaviour of the hill has been attempted by using a three-dimensional, elastic FEM model. As a first result, significant modifications of the seismic action are to be expected due to hill morphology and soil profile. Moreover, owing to specific mode shapes of the hill, local stress concentrations can occur within the varicoloured clay along the contact with the overlying conglomerates.

CONCLUSIONS

Within the limits set by the size and complexity of the phenomena being examined, this research gives a contribution to the knowledge of the effects of earthquakes on the behaviour of natural hillslopes consisting of overconsolidated and structurally complex clayey soils.

Some remarks having general validity can be made on the basis of this ongoing study.

The slide have occurred in zones where ancient, quiescent complex slides already existed, and involved large amounts of heterogeneous soils.

The large movements became evident with some delay with respect to the main shock and the development of the slides was slow and gradual.

Thus, it may be inferred that before the earthquake the safety margin of the hillsides was low and therefore it is very likely that a long-lasting seismic action (50-80 s) may have produced failure conditions due to an increase in the tangential stresses in the slope portions where the initial stresses were greatest. The failure process successively expanded both in time and space thus causing the general failure of the slope.

Besides being governed by forces of inertia, also small increases in pore pressure may have contributed; given the gradual development of the process, it is however to be ruled out that extensive and widespread liquefaction phenomena may have played some role.

The deformation phenomena observed in the Bisaccia Hill may be explained on the basis of the hill shape and of the soil succession.

These induce high stress levels in the clays underlying the conglomerate. During the earthquake, stresses induced by the actions triggered by the dynamic response of the "slab-and-clay" system increase the initial state of stress. Thus viscous deformation phenomena are activated in the clays which wear off in time.

REFERENCES

AGI (1979). Some Italian Experiences on the Mechanical Characterization of Structurally Complex Formations. Proc. 4th ICRM, 1, 827-846, Montreux.

Cotecchia,V. (1982). Phenomena of Ground Instability Produced by the Earthquake of November 23rd, 1980 in Southern Italy. Proc. 4th Int.Congress of I.A.E.G.,New Delhi.

Cotecchia,V., Travaglini,G., Melidoro,G. (1969). I movimenti franosi e gli sconvolgimenti della rete idrografica prodotti in Calabria dal terremoto del 1783. Geol. Appl. e Idrogeol., 4, 1-24.

D'Elia,B. (1983). La stabilità dei pendii naturali in condizioni sismiche. Proc. XV Convegno Nazionale di Geotecnica, Spoleto.

Pellegrino,A., Picarelli,L. (1984). Formazioni argillose intensamente tettonizzate. Contributo alla caratterizzazione geotecnica. Geol.Appl.e Idrogeol.(in press).

Seed,H.B., Idriss,I.M. (1970). Soil Moduli Factors for Dynamic Response Analysis. Report No. 70-10, Univ.of California, Berkeley.

ACKNOWLEDGEMENTS

This study has been carried out with the financial support of the Ministero della Pubblica Istruzione