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Geotechnical problems caused by glaciolacustrine clays in the French Alps

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ABSTRACT

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After more than 10 years of observations and monitoring of several landslides in glaciolacustrine clays in the French Alps, the authors give an account of the physical and mechanical characteristics of these formations. The physical and geomechanical properties of the clays are analysed in relation to the main types of instability observed on the natural slopes of the area studied. The low plasticity indexes of these clays explain the rapid transformation of the clays into a liquid state leading to innummerable surface flows. The clays show a strong anisotropy at peak strength conditions that disappears at residual strength ($c' = o$; $\phi' = 16$–$18°$). Natural slopes become unstable if the gradient exceeds 8–10°. Three types of movement can be distinguished at three different depths (0–5 m; 5–10 m and greater than 10 m). The displacement rates vary from 1 cm/yr for the deep-seated slides to as much as 1 m/yr for the surficial slides. Displacement rates in these slides are limited by the viscous properties of the laminated clays. However, extreme rainfall may cause catastrophic failure. In conclusion, some recommendations are given from an engineering point of view.

INTRODUCTION

Glaciolacustrine clays are commonly encountered in the valleys of the Alps. These Quaternary clays, which were deposited in glacially dammed lakes, are very different — in their structure, mineralogy and mechanical characteristics — from the North American clays (sensitive clays and varved clays) which were mainly deposited under marine conditions (Parsons, 1976; Tavenas et al., 1979).

In the Alps of the Dauphiné, the Trièves region about 40 km south of Grenoble is of particular interest (Fig.1). The clays in this sector, which outcrop to a maximum altitude of 750 m, were deposited in a glacially dammed lake covering an area of about 300 km^2, impounded by the Isère glacier during the Würm maximum episode. Because of the very uneven relief of the substratum in the basin where the sedimenta-

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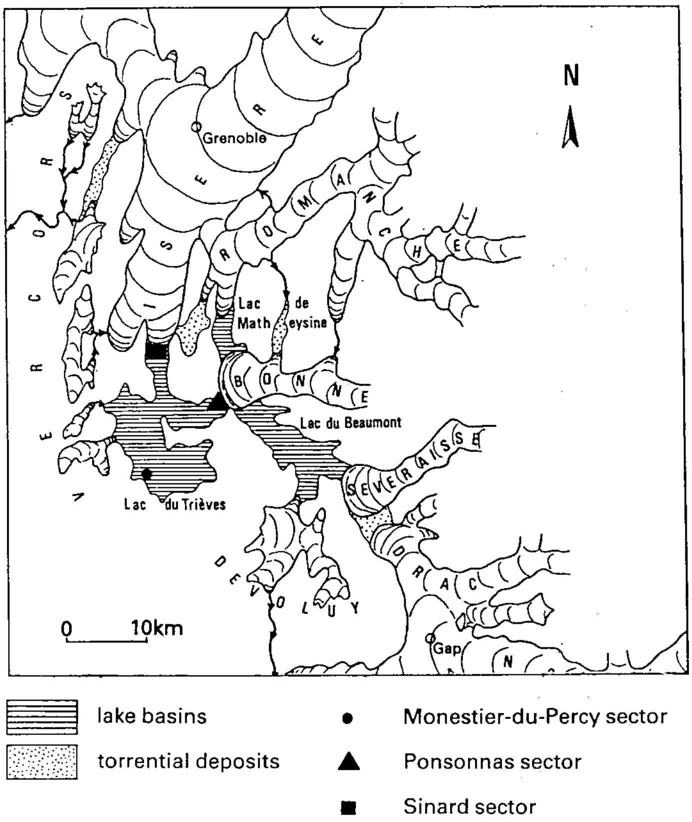

Fig.1. Extent of the glaciers at the Würm stage maximum and location of the glacial barrier of Trièves (according to Monjuvent, 1973).

tion took place, the thickness of these clays can vary greatly over short distances, from zero to a maximum of 200 m (Monjuvent, 1973; Antoine et al., 1981).

In the Trièves region, which was studied in particular detail, the fact that the stream network has cut deeply into the formations means that these clays now form the greater part of the valley slopes, and their geotechnical characteristics result in numerous signs of instability.

IDENTIFICATION AND PHYSICAL PROPERTIES OF THE CLAY MATERIAL

The clays, sometimes referred to as varved or laminated clays, have a silty clay texture and are characterised by a marked anisotropy, i.e. finely laminated partings; with light coloured (silty) beds alternating with dark coloured (clayey) beds. The thickness of these laminae is variable (1 mm–10 cm), but they are generally horizontal.

The term "varved" commonly refers to a strictly seasonal sequence of deposits. According to observations of what is occurring at present, many layers could be deposited within a single year. For example, complete drainage of the Chambon reservoir in 1980 provided the opportunity to study the sediments deposited in the lake during the previous 45 years (Sikirdji, 1982). This study revealed facies which were similar to the Trièves clays, suggesting that the term "varved" should be used without any suggestion as to the (as yet unknown) rhythm of formation of the deposits.

Mineralogy

Material investigations with respect to geotechnical and physical characteristics were carried out in three different areas (Fig.1). These three areas differ, especially in their mineral content (Table I), which is related to the differences in lithology of the surrounding relief, varying from crystalline to sedimentary rocks. Among the non-clayey minerals calcite and quartz predominate, together with some feldspars. The predominant clay minerals are illite and chlorite, commonly accompanied by swelling, interstratified materials in small quantities, as confirmed by the relatively low values of the plasticity indices (see below).

Physical identification

Grain size analyses of the Trièves clays show that particles smaller than 2µ make up 40% of the light-coloured beds and 60% of the dark beds, so these are classified as clayey silts (Fig.2).

The dry density is of the order of 15–16 kN/m^3, which corresponds to a porosity of approximately 40%. Specific gravity of the particles has a mean of about 2.6. The measured values of the Atterberg limits vary between 30% and 48% for the liquid limit, and between 10% and 25% for the plasticity index (Fig.3).

A relatively low plasticity index means that the liquid limit is quickly reached near the surface, under the natural fluctuations of moisture content. These laminated clays are therefore subject to transition from the plastic state to the liquid state as the moisture content increases, which explains the innumerable solifluction flows,

TABLE I

Mineralogical composition of the laminated Trièves clays

Mineral composition	Monestier-du-Percy sector	Ponsonnas sector	Sinard sector
Quartz (%)	10–20	–	14–16
Calcite (%)	25–50	50–70	15–20
Feldspar (%)	5–10	10–20	5–10
Illite (%)	10–15	–	42–47
Chlorite (%)	6–10	–	14–16
Kaolinite (%)	5–6	–	–
Montmorillonite (%)	5–12	–	0–5
Vermiculite (%)	–	20–30	–

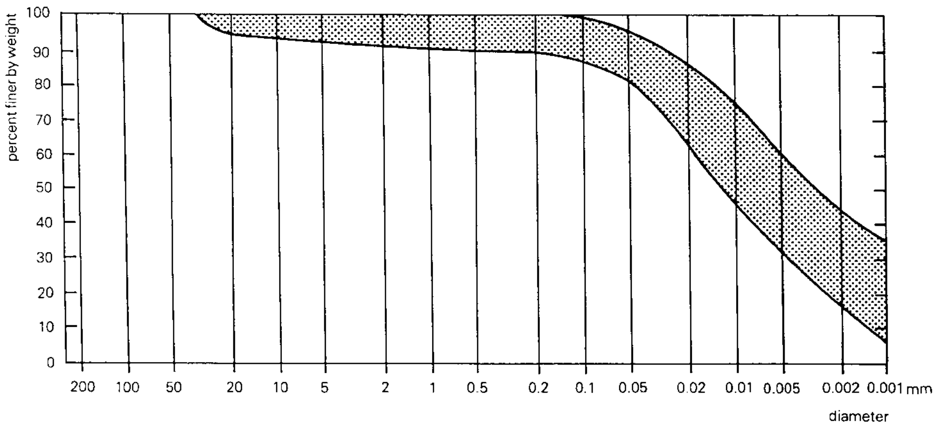

Fig.2. The grading range of laminated clays.

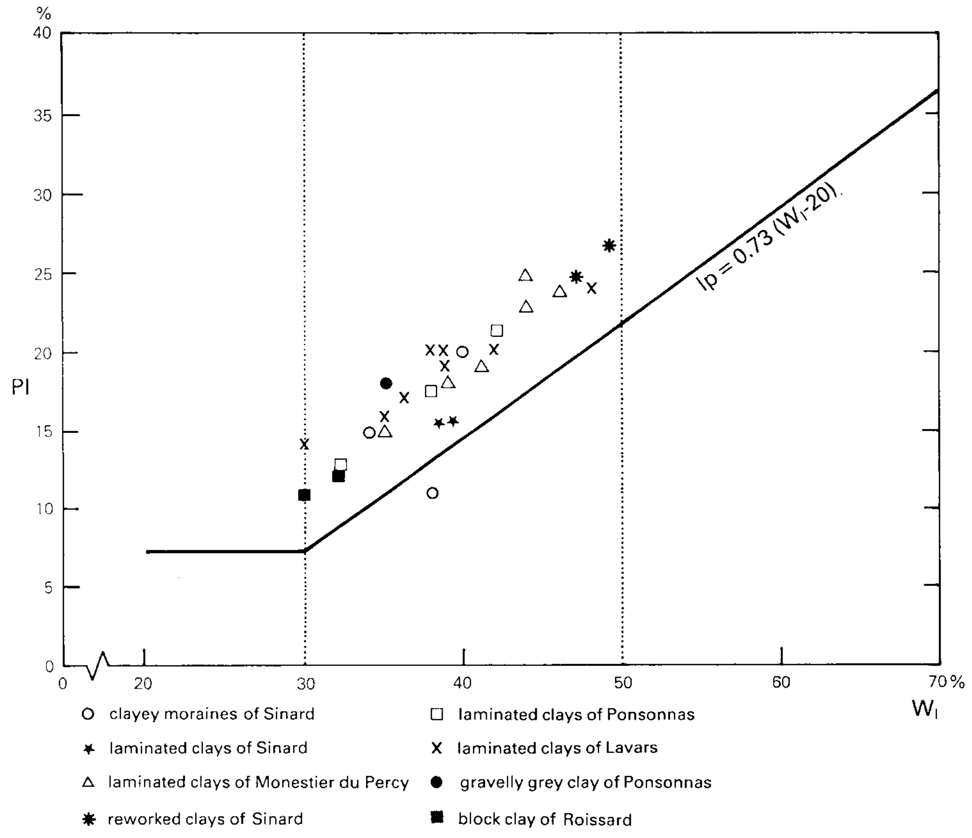

Fig.3. Plasticity diagram of the Trièves clayey formations (after Vuillermet, 1989). PI = plasticity index; W_l = liquid limit.

observed at the surface as well as the rapid transformation of the slide front into a mud flow.

In addition, the textural anisotropy explains why the permeability may be estimated at about 10^{-10} m/s perpendicular to the bedding planes, and on the order of 10^{-8} m/s parallel to these planes (Nieuwenhuis and Van Genuchten, 1986).

The anisotropy of these clays is also reflected by the differences in seismic velocities, which give a 12% difference in velocity perpendicular to (greatest) and parallel to the lamination. In general, velocities measured in the laboratory and the field range between 1000 and 2000 m/s. For disturbed varved clays, velocities never exceed 1200 m/s; this is ascribed to their greater porosity. Resistivity values measured in undisturbed clays vary between 10 and 70 Ohm·m; whereas in disturbed material greater ranges are measured, varying from 20–250 Ohm·m. These velocity values are more scattered owing to greater variations in the water content of the clays.

GEOMECHANICAL CHARACTERISTICS

The anisotropy of the laminated clays is clearly demonstrated in all types of strength measurements. Table II shows a survey of the results for the different sites. Triaxial consolidated drained (CD) tests show peak ϕ' values varying from 23–26°. Somewhat lesser ϕ' values for triaxial CD tests were found where the slip planes develop along the laminae (20–21°). The anisotropic character is especially expressed by the differences in cohesion: 1–5 kPa along the laminae, and 13–23 kPa normal to them. Direct shear tests along laminae show the same cohesion measured by

TABLE II

Mechanical characteristics of the laminated Trièves clays (averaged over 3 different areas)

Parameter	Value	Test	Remarks
Peak ϕ values (°)	23–26	CD triaxial	across laminae
	20–21	CD triaxial	along laminae
	22–23	CD direct shear	along laminae
	20–23	Back analysis	
Residual ϕ values (°)	18–19	CD direct shear	
	17–19	Back analysis	
Peak C values (kPa)	13–23	CD triaxial	across laminae
	1– 5	CD triaxial	along laminae
	1– 5	CD direct shear	along/across laminae
	29–40	Back analysis	
Residual C values (kPa)	0	CD direct shear	across-along laminae
	6– 7	Back analysis	
Undrained cohesion (kPa)	46–68	UU triaxial	across laminae
	30–42	UU triaxial	along laminae
Dynamic viscosity coefficient (kPa·s)	2.5×10^8	CD direct shear	continuous creep
	1.4×10^3	CD direct shear	slip plane
Overconsolidation ratio — OCR (-)	13–20	Oedometer	
Elastic modulus (MPa)	1– 5	Pressiometer	disturbed
	10–60	Pressiometer	undisturbed

triaxial testing but the ϕ' values are somewhat greater and more scattered. This might be ascribed to the fact that in the triaxial tests the slip plane can freely develop in the (weaker) clay laminae; whereas in direct shear tests the slip plane is forced either through a clay or across a silt layer (Van Genuchten, 1989). Undrained unconsolidated (UU) tests at various sites show a difference in undrained cohesion values of as much as a factor 2 between shearing along and across the laminae.

Residual values were measured by reversal direct shear tests and show a reduction of the c' (CD) value to practically zero and a lower ϕ' (CD). It is interesting to note that direct shear reversal tests carried out perpendicular to the laminae show a disappearance of anisotropy after a deformation of about 0.4 m (Van Genuchten, 1989). This is especially important because many monitored slides (see below) are in a more or less residual state of strength.

A number of back analyses have been carried out on different slides in the laminated clay using various techniques (Al Hayari, 1989) in order to get a better idea of the mean strength characteristics on a large scale as well as to validate the strength results of laboratory tests on smaller samples. One uncertainty of back analysis methodologies is the form of the slip plane and the hydrological conditions. It is, however, striking that the peak strength and residual strength characteristics obtained by these methods are in good agreement with the laboratory results (see Table II).

Special attention was given at the Ponsonnas sites to the viscous character of the clay, which may be responsible for the flow phenomena detected particularly in the upper zone of the laminated clays. A viscosity coefficient on the order of 2.5×10^8 kPa·s has been established by creep tests in the direct shear box (Van Asch, 1984) for non sheared clays. In addition, the sheared material in the slip plane has a viscous component which contributes to the strength during slope movement. Direct shear tests on pre-sheared clays, measuring the strength at different strain velocities, revealed a dynamic viscosity coefficient in the slip plane which was related to the effective normal stress. From these tests a dynamic viscosity of 1.4×10^3 kPa·s was calculated for slip planes at a depth of 4 m (Van Genuchten, 1989).

Oedometer tests were carried out in order to assess the degree of overconsolidation of these clays. Samples taken from a depth of 3–4 m show clear overconsolidation characteristics with overconsolidation ratios (OCR's) between 13 and 20. In situ pressiometric tests show E values of 1–5 MPa in completely disturbed varved clay at the surface, and 10–60 MPa in undisturbed laminated clays.

MAIN TYPES OF INSTABILITY

Observed phenomena

Numerous observations indicate that natural slopes in the laminated clays show signs of instability if the gradient exceeds 8–10°. Three types of movement may be distinguished, and may or may not occur simultaneously (Fig.4):

(1) surface movements (at depths of 0–5 m);
(2) planar movements (at depths of 5–10 m),
(3) deep movements of a rotational type (depths greater than 10 m).

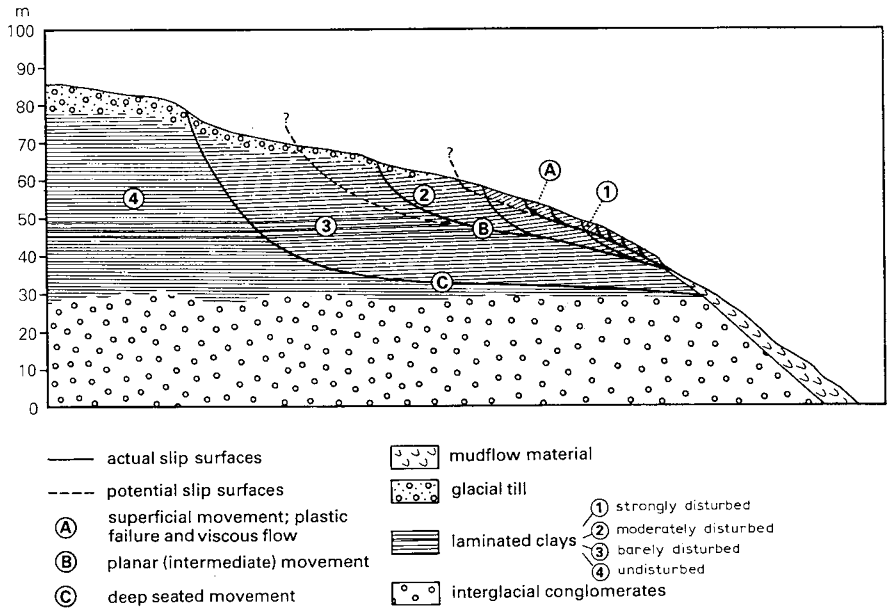

Fig.4. Idealized section across a slope in laminated clays to show potentional and actual slip surfaces.

Mechanisms

Surface movements

Surface movements are related to the relatively low plasticity indices, and are subject to rapid transformation from the plastic to the liquid state as the moisture content increases. This results in the development of slow to more-or-less rapid mudflows with a dominant viscous component. They can be distinguished by their typical lobate shape wherein the original laminated structure has been completely destroyed.

Planar sliding with rupture surface parallel to the slope

These movements relate to dissection of the formation into vertical slices. This dissection is initiated by shrinkage cracks, which open in the surfaces exposed to air. This facilitates an increase in the interstitial pressure by direct penetration of water from precipitation or snow melt. This phenomenon occurs periodically; the slightest widening of the fissures causes the pore pressure to drop, and is restored only after a certain lapse of time (Nieuwenhuis and Van Genuchten, 1986). This pore pressure, which is transmitted through the silty beds confined between the clayey beds, may be slightly artesian (Van Genuchten and Van Asch, 1988).

Detailed studies, based on continuous recordings, during the last 8 years in the Ponsonnas sector (Fig.5), have confirmed that these mass movements are intermittent over the time scale of 1 yr, 1 month, 1 day and even 1 h. Rain or meltwater is the main driving force behind these movements. The cumulative displacement of the masses shows a quite good correlation with the effective precipitation totalled over winter and spring.

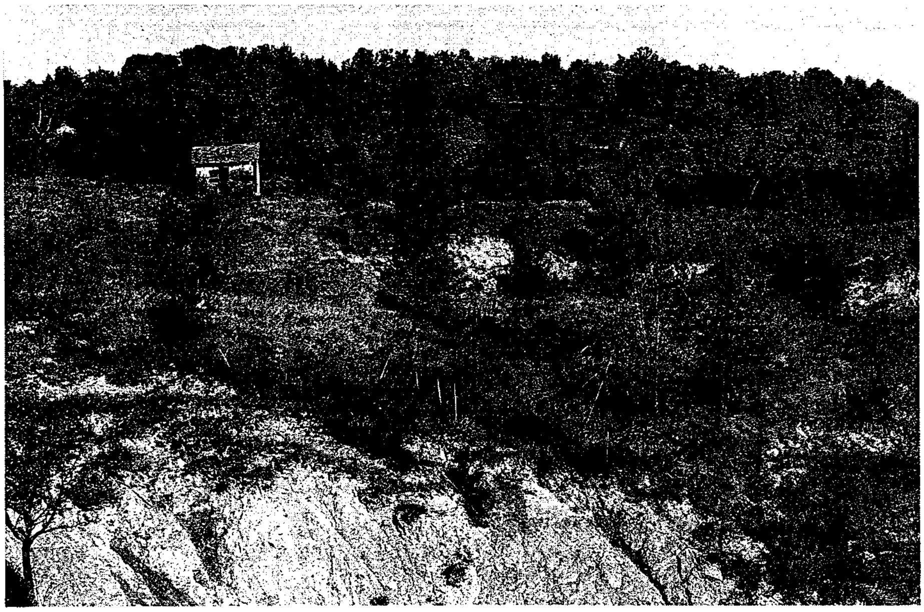

Fig.5. View of the Ponsonnas slide.

At the hourly time scale, movements depend on the variations in pore pressure within the sliding plane, which are affected by block movements. These planar movements may be blocked temporarily by irregularities on the sliding surface, or by the accumulation of materials at the foot of the slide (Nieuwenhuis, 1988; Van Genuchten, 1988; Van Genuchten and Van Asch, 1988). It appears that in these planar slides a slight excess of shear stress can be compensated by a viscosity component in the shear plane, which results in slow movements of around 2 cm/day. However, extreme rainfall may cause catastrophic failure. In fact, the deep seated slide of Harmalières (see below) may illustrate such behaviour as well.

Deep sliding of the rotational type

Shearing across the laminae can also occur, as these materials are homogeneous despite their anisotropy, and rotational slides can thus develop into more complex shapes. There are several spectacular examples of this phenomenon (Antoine et al., 1988).

(a) The Monestier-du-Percy slide (Fig.6). This slide, which occurred in April 1978, affected a total area of 9 ha of gently sloping pasture land (12°) (Giraud et al., 1980). In the centre of the slide, the thickness of the reworked material was estimated at about 20 m by seismic prospection. The lower part of the destabilised zone seems to have been subjected to generalised planar flow, with substantial horizontal translations (about 70 m at certain locations).

(b) The Combe d'Harmalières slide (south-east of Sinard). This slide, which occurred in March 1981, also affected an area of gently sloping pasture land (13°), encompassing approximately 50 ha. The estimated depth of the slide surface, at the

Fig.6. View of the Monestier-du-Percy slide.

deepest point, is about 45 m (Al Hayari and Blanchet, 1988). The lower part of this slide became a mud flow, discharging into the Monteynard reservoir. The volume of materials thus suddenly entering the reservoir at the time of slope failure was estimated by Electricité de France at 250,000 m^3 (Fig.7).

(c) The slide at the Mas d'Avignonet housing estate (east of Sinard). In addition to surface movements observed at this housing estate (mean depth below 5 m), which caused serious damage to buildings, inclinometer measurements showed evidence of deeper movements. A slide surface was thus detected at a depth of about 11 m, as well as another surface at a depth of 43 m; the latter could be an indication of reactivation of an old movement, the existence of which was suggested by morphological analysis (Antoine et al., 1987, 1988; Blanchet, 1988).

CONCLUSIONS AND RECOMMENDATIONS

Glaciolacustrine laminated clays occur in many places in the French Alps and fill basins of glacial origin. In the Trièves area, a majority of natural slopes are developed on these laminated clays. Because of their geotechnical characteristics, these clays induce much surficial instability with damaging consequences for farmland, roads and urban areas (Besson, 1983). In this region, 7000 ha are affectd by these surficial movements, which occur over an average total surface of 11%, and as much as 60% in some townships (Moulin, 1985). These surficial slides are triggered by rain and melting snow. This implies that all earthworks must be constructed during the dry season.

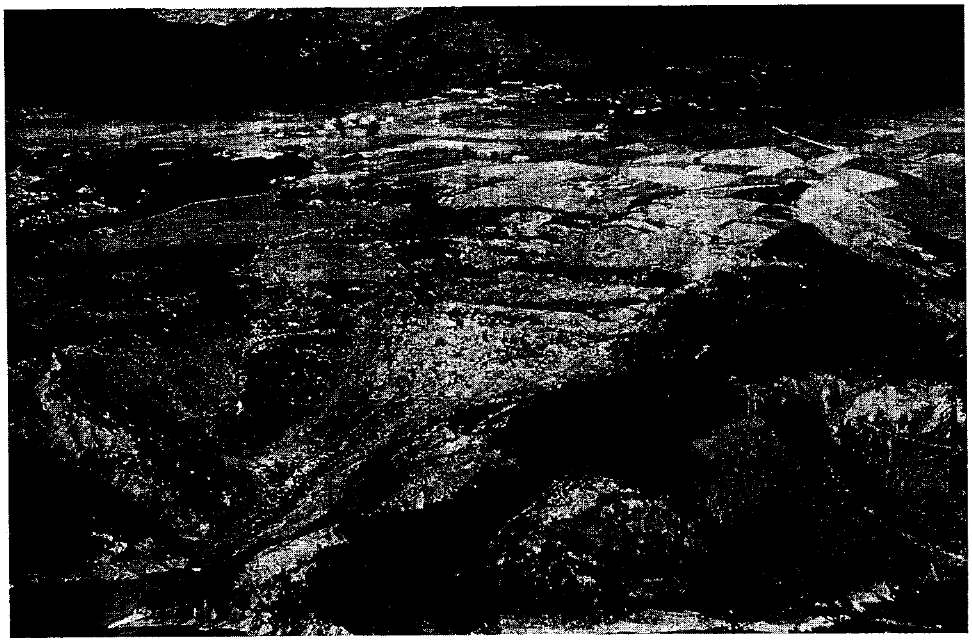

Fig.7. View of the Combe d'Harmalières slide.

The surficial behaviour of these clays is strongly dependent on water content. At the end of a dry period, many cracks and fissures develop and facilitate rapid subsurface intrusion of rainwater. Conversely, the behaviour of these clays at depth is very different, as water percolation slows down because of lower permeability. It is important to point out that, because of anisotropy, some local uplift phenomena could occur during wet periods and lead to instability.

From an engineering standpoint, this implies that the surficial formations are very unstable but can be stabilized by artificial drainage. Deep-seated slides move less frequently and are less likely to be stabilized. For practical applications it is important to stress the viscous characteristics of these clays, which implies that classical plastic failure at peak strength conditions is of relatively secondary importance. It may be useful to note that peak strength in a landslide area is a value of limited importance. In practice, the strength along the slide planes is somewhere between the peak and residual strength, whereas displacement rates are limited by the viscous properties of the laminated clays. If necessary, one can use the residual strength characteristics of these clays for stability analyses ($c' = 0$, $\phi' = 16$–$18°$).

The displacement velocities of these slides range from 1 cm/yr for the deep-seated, to as much as 1 m/yr and more for the surficial slides. For the latter, slope angle and water content are the most important factors and facilitate the potential hazards forecast. It is, however, difficult to predict catastrophic ruptures for the deep-seated slides, which represent an important threat to public security.

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