ELSEVIER

Engineering Geology 40 (1995) 223–234

ENGINEERING GEOLOGY

Geological and geotechnical properties of the "Terres Noires" in southeastern France: Weathering, erosion, solid transport and instability

P. Antoine [a], A. Giraud [a] *, M. Meunier [b], T.Van Asch [c]

[a] *Institut de Recherches Interdisciplinaires de Géologie et de Mécanique, BP 53X, 38041 Grenoble Cedex, France*
[b] *Cemagref, BP 76, 38042 Saint Martin d'Hères Cedex, France*
[c] *Department of Physical Geography, Utrecht State University, P.O. Box 80115, 3808 TC Utrecht, The Netherlands*

Received 21 February 1995; accepted 31 July 1995

Abstract

The geological formation known as the "Terres Noires" covers large areas of southeastern France, between the Rhône valley and the pre-Alpine hills. This formation consists mainly of dark marls of the basal Upper Jurassic. These marls are very susceptibility to weathering and are particularly prone to erosion, resulting in high solid transport. This paper attempts to quantify this transport in experimental catchment areas, and shows that a forest cover can play a major role in preventing this type of phenomenon. Weathering of this formation may also lead to gravity instabilities in fresh marl (although this is rare) and, much more frequently, in the surficial weathered material.

1. Introduction

A predominantly marly, dark formation is found in southeastern France with a thickness exceeding 2000 m in places. The formation is generally known as the "Terres Noires" and was deposited during the Jurassic in an extensive basin. The current boundaries of this basin are approximately delineated by the Rhône Valley to the west, the latitude of Grenoble to the north, the front of the internal Alps to the east and the ridges of the Provence to the south.

This formation is known for its high susceptibility to weathering and erosion, its instability and its tendency to supply solid material to watercourses.

This article analyses the weatherability of the material and its role in erosion, solid transport and surface instability. Analysis of the last two aspects is based on the results of field measurements conducted at experimental sites located in the Digne and Barcelonnette regions (Fig. 1).

2. Stratigraphy

Stratigraphic studies (Artru, 1972) have shown that the "Terres Noires" can be subdivided into two units, both essentially marly, separated by a harder median marker layer:

(1) The lower unit (upper Bajocian to lower Bathonian) consists of black marls, cut into fine platelets;

* Corresponding author.

0013-7952/95/$09.50
SSDI 0013-7952(95)00053-4

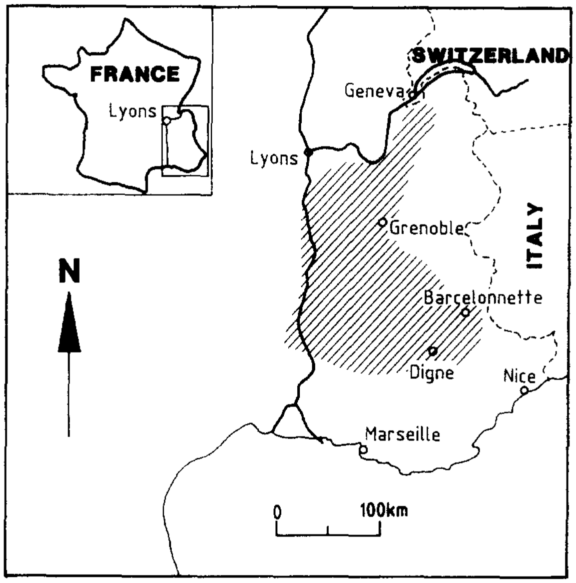

Fig. 1. Location map showing the extent of the "Terres Noires".

(2) The marker layer (upper Bathonian and lower Callovian) is harder, acts as a good reference layer, and consists of clayey, occasionally dolomitic limestone, with a brownish patina; and

(3) The upper unit (lower Callovian to the middle Oxfordian) also consisting of marls cut into platelets, with carbonated nodules.

Except for a few minor differences, this subdivision can be found throughout the area under consideration.

3. Characteristics of the "Terres Noires"

The "Terres Noires" consists of highly stratified rocks, often exhibiting a fine bedding inherited from their original deposition by turbidity currents. They include a detrital and a carbonated phase.

From recent research on the physical and mineralogical properties of the formation, it was concluded that the lower and upper units of the stratigraphic series are very similar. The "Terres Noires" can, therefore, be considered as a homogeneous lithological mass with average characteristics as defined by Phan Thi San Ha (1992).

The carbonate content (made up essentially of calcite) varies from 20 to 80% of the total volume, with corresponding facies ranging from marls to clayey limestones. The detrital phase comprisess mainly silt (predominantly quartz) with a small proportion of clayey materials (mainly illite). The plasticity indices measured on the fine fraction average 11%, thus confirming the silty nature of the detrital fraction. In addition, methylene blue tests reveal an almost total absence of smectites, found only in small quantities in interstratified minerals.

4. Weathering processes

4.1. Field observations

Areas devoid of vegetation revealed the following structure of the weathered zone:

(1) A soft, disorganised, surface zone (some ten cm thick) consisting of loose marl platelets;

(2) An intermediate unit (up to 50 cm thick), in which the laminated structure of the "Terres Noires" is preserved, marking the transition between sound parent rock and the completely weathered surface zone; and

(3) Intact rock, 30 to 50 cm below the surface (determined by portable penetrometer tests, Dumollard, 1984).

In areas with a dense vegetation cover, the weathered zone is much thicker, and in some places, exceeds several metres. In such cases, horizontal landslides may occur at the contact with the underlying intact bedrock, affecting on the forest cover.

4.2. Analysis of the phenomenon

4.2.1. General

The "Terres Noires" exposed at the surface are continually subjected to physical weathering processes, producing a loose material consisting of fine platelets (ranging in size from a few mm to some cm). Eventually, the highly decalcified platelets are totally disintegrated by water seepage. They then form a silty overlayer with a particle size close to that of the original sediment.

Phan Thi San Ha (1992) carried out laboratory tests on weathering phenomena by subjecting the rock to alternating wet and dry cycles. After four cycles, the laboratory material clearly resembles the naturally weathered products collected on the marl slopes. After ten cycles, the sieve curves of the natural product (Fig. 2a) and the product obtained from the weathering test (Fig. 2b) are found to be very similar. In this case, the curves tend to shift towards finer values which indicates a reduction in the mean particle size without changing the size distribution. The fragmentation process does not change. On the other hand, wet sieve analysis leads to total dissociation of the material accompanied by a certain change in the shape of the curve. This change in shape is easier to detect with the naturally weathered product compared to the lab-tested product. Although care should be taken when comparing curves resulting from different processes, the wet sieve curve shown in Fig. 2a is indicative for a material sedimented by settling, probably corresponding to the initial marine deposit. The highly permeable near-surface weathered material is subjected to water circulation whereas the underlying unweathered marl is largely impermeable. Various physical and chemical actions affect the weathered layer, especially the loose surface material. When the slope is steep and rainfall is heavy, numerous erosion gullies transport loose surface material to the streams (bed load). The distribution of the gullies appears to be random. The remaining loose surface materials are subjected to infiltration and slow percolation (especially with moderate rainfall). Decalcification of the permeable weathered horizons liberates the calcite which is then carried by the water and is deposited at the lower parts of the slopes, where the subsurface circulation emerges. Here, the calcite tends to form a very crumbly cement between the platelets. Overall, a process of calcite depletion occurs in the parent rock at the upper part of the slopes, with calcite enrichment in the weathered surface layer at the valley bottom (Phan Thi San Ha, 1992). The material accumulated at the valley bottom thus tends to obtain a certain degree of cohesion which may reduce the erosion and the effects of sheet runoff. This decalcification process is determined by calcimetry and confirmed by scanning electron microscopy, showing the pores resulting from the dissolution of calcite. The increase in porosity from intact rock to weathered rock (honeycomb texture) confirms these observations. A 20–30% reduction in carbonate content may cause a fourfold increase in porosity (Phan Thi San Ha, 1992).

4.2.2. A special case

Locally, and exclusively in the vicinity of Barcelonnette, the visual appearance of rocks transported by landslides in the "Terres Noires" are unique owing to intense weathering. These rocks seem to have swollen and are subsequently flaked and transformed into a mass of fine materials which flow at the surface (Fig. 3). Similar behaviour was observed in smectite-rich weathered

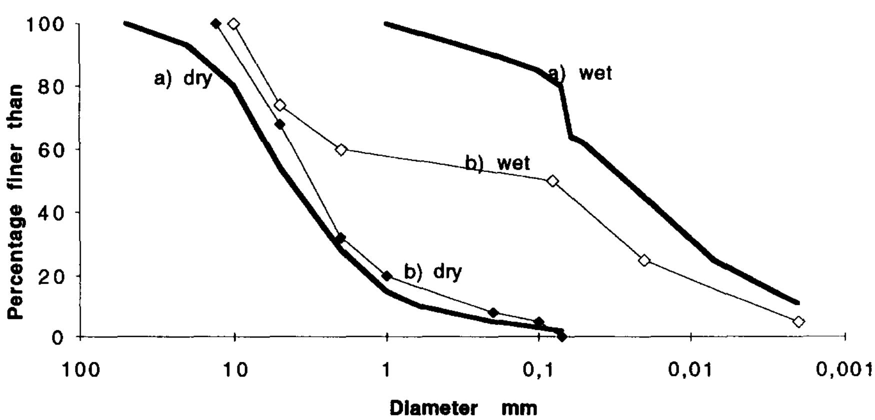

Fig. 2. Dry and wet sieve curves: a) on the natural weathering product of the "Terres Noires". b) by 10-cycle weathering test.

Fig. 3. Photograph showing weathering of the "Terres Noires".

volcanites on the island of Reunion caused by swelling. In this case another explanation must be found (because there are no significant quantities of smectites). Scanning electron microscopy revealed a certain content of pyritic microgranules. Through oxidation and hydration, these microgranules generate two separate phenomena: (a) high-speed swelling of rocks exposed to water, leading to accelerated production of fine materials, (b) production of small quantities of sulphuric acid which contributes to the decalcification of the facies by the formation of gypsum.

5. Runoff/erosion processes

The "Terres Noires" formation displays the same morphology as badlands (Descroix, 1985), characterised by steep, rounded ridges, with vertical sides ("elephant's back"), generated by a dense drainage network because of their almost total impermeability. A specific erosion process occurs in these areas, promoted by the rapid disintegration of the material through weathering (cf. Section 4). This causes voluminous solid transport (cf. Section 6) and, in some cases, promotes surfacial instability (cf. Section 7).

5.1. Non-localized surface erosion

It has already been shown (cf. Section 4.2) that weathering of the "Terres Noires" is a continuous process. During periods of no runoff (especially in dry winters), the fine materials generated by weathering provide a considerable amount of surficial sediment available for transport by the first heavy shower; the muddy runoff collects in reaches of the local watercourses, and is then transported downstream.

Saturation of the weathered layer may cause solifluction. This mainly occurs on steep valley slopes at the end of winters when abundant snow has fallen, generating small mudslides and mudflows which also supply the reaches. The solifluction bulges are generally small and localized; however, because they occur in many places in the catchment area, they may be considered as a non-localized process. (This hypothesis was adopted when interpreting the measurements.)

These two processes (supply of a considerable amount of loose material and saturation of this weathered material) explain why the first major spring event always causes a flood with a high level of solid transport, and sometimes even a debris flow.

Other important events are storms with high rainfall intensities which destroy the structure of the weathered layers, partly through splash effects, promote marl platelet degradation into silt products and facilitate material transport by surface runoff. Runoff tends to accumulate in small temporary gullies cut out in the valley slopes, finally discharging into the permanent drainage channels. In these small gullies, the solid transport can be so strongly concentrated that the flow becomes a miniature debris flow (Oostwoud Wijdenes and Ergenzinger, 1995).

Because this non-localized surface erosion occurs with each flood, it occurs much more frequent than localized erosion (cf. Section 5.2). This explains that erosion volumes on valley slopes are closely related to the intensity and kinetic energy of the rainfall (Borges, 1993).

5.2. Localized erosion

This type of erosion consists essentially of very localized falls of debris from more calcified layers which protrude as the result of faster erosion of the more marly underlying layers. This process is not necessarily linked to a specific rainfall event.

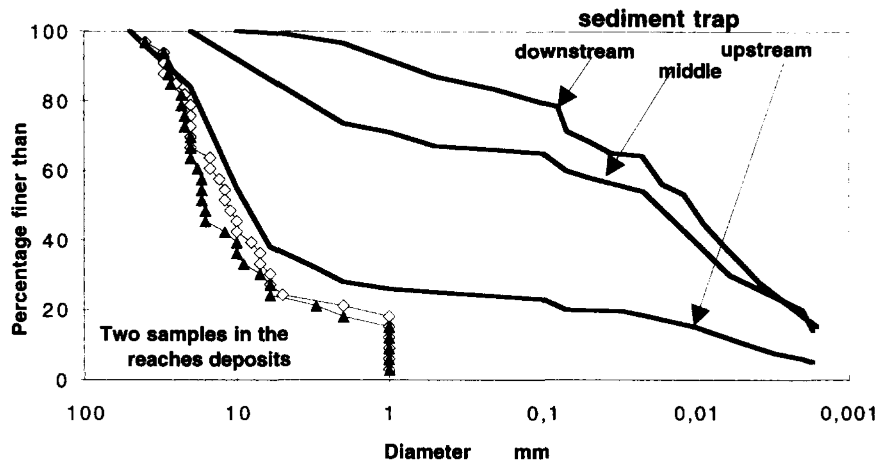

Fig. 4. Sieve curves of deposits in the sediment trap of the Laval basin.

5.3. Erosion quantification

The experimental catchment areas developed at Draix (southeastern France, 15 km northeast of Digne, Fig. 1) were used to quantify erosion. Solid transport was measured by two systems: (1) a sediment trap storing all coarse sediments, and some of the fine sediment, as shown by the sieve curve (Fig. 4); and (b) automatic samplers located downstream of the filter dam, providing continuous measurements of fines carried by the water.

The measurement operations, the difficulties involved and the methods proposed for critical analyses of the data and estimation of missing data are described in Mathys and Meunier, 1989, Cambon et al., 1990, and Borges, 1993.

The physiographical characteristics of the three catchment areas are given in Table 1.

Table 1
Physiographical characteristics of the three Draix ERB catchment areas

Basin	Surface (hectares)	Mean slope (%)	Bareness rate (%)	First year of data
Roubine	0.1330	45	80	1984
Laval	86	22	78	1984
Brusquet	108	26	13	1987

(1) The Roubine is an order 0[1] basin which may be considered as a geomorphological unit representative of the erosion processes: the slope of the main reach (about 35% at the outlet) is too steep to allow intermediate hydraulic deposits in the reaches. The rain recording parameters explain the erosion production very well (Borges, 1993).

(2) The Laval is an order 1 basin and consists of several sub-catchments discharging into a drainage channel about 1 km long, with a slope varying from 8 to 4%. Erosion, deposition and re-transport thus occur with each flood. This explains the necessity for flow parameters to explain the erosion volumes.

(3) The surface area of the Brusquet is slightly greater than that of the Laval; however, it is almost entirely covered with forest and thus offers, by comparison with Laval, an ideal opportunity to study the effects of the forest on floods and erosion.

Annual volumes (in tonnes/ha year) are given in Table 2. The values obtained for the Brusquet in 1988–1990 are interannual values, because the trapped volumes were too small to be measured annually. The clear increase noted from 1992 is due to the construction of a forest track. Despite the fact that the values for the Laval catchment for 1992 had to be estimated for the two months

[1]A channel of order n has one or several tributaries of order lower than n and a maximum of one tributary of order n.

Table 2
Annual erosion, mean and standard deviation, in Draix ERB (t/ha year)

	1985	1986	1987	1988	1989	1990	1991	1992	1993	**m**	**s**
Roubine	118	262	163	174	89	138	132	350	163	**177**	**81**
Laval	91.3	159	166	103	64	181	135	(311)	176	**154**	**71**
Brusquet				2[a]	2[a]	2[a]	3	8	7	**4**	**x**

[a]Average of three years.

when no data were obtained, it was nonetheless taken into account in the statistical calculations.

It can be seen that the erosion values measured on the denuded "Terres Noires" exceed 100 t/ha year, which is the value found for some of the most erodible soils in the world (Walling, 1988; Mahmood, 1987).

Table 2 shows that, in terms of erosion per hectare of denuded ground, the mean annual erosion rate is approximately the same in the large and small catchment areas with a light vegetation cover, although considerable variations may arise in a given year. With dense vegetation, however, the degraded surfaces are spread over the entire catchment area and the erosion products cannot be easily transported to the drainage network. Consequently, the erosion per hectare is up to fifty times lower than that measured on denuded basins.

The annual erosion rate on denuded ground varies from one year to the next. The data obtained fit Gumbel's law fairly well (Fig. 5); an erosion rate of 10-year return period is of the order of 220 to 270 t/ha year.

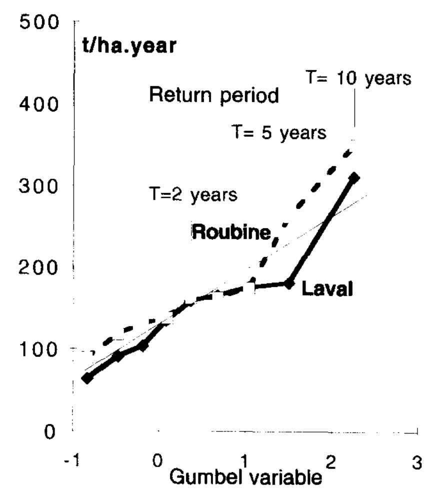

Fig. 5. Statistical law of annual erosion in the Draix ERB.

6. Solid transport

The erosion processes described in Section 4 above are complicated by the hydraulic phenomena which occur in the drainage channel (temporary storage of sediments, deposition and retransportation along the reaches). If solid transport processes are to be modelled, it will be necessary to combine a hydrological flood simulation model, an erosion model, and, finally, a solid transport model (Borges et al., 1994). The system would, thus, be highly dependent on the nature of the flow, i.e., the type of mixture and its behaviour.

6.1. Composition

Because the marl platelets disintegrate easily, the particle size distribution of the transported solids changes considerably during the transport process, leading rapidly to a predominance of fine materials. The ratio of the volume of materials

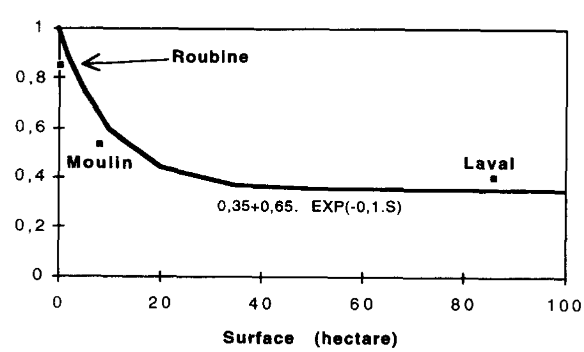

Fig. 6. Variation in Deposited volume/Total sediment volume ratio.

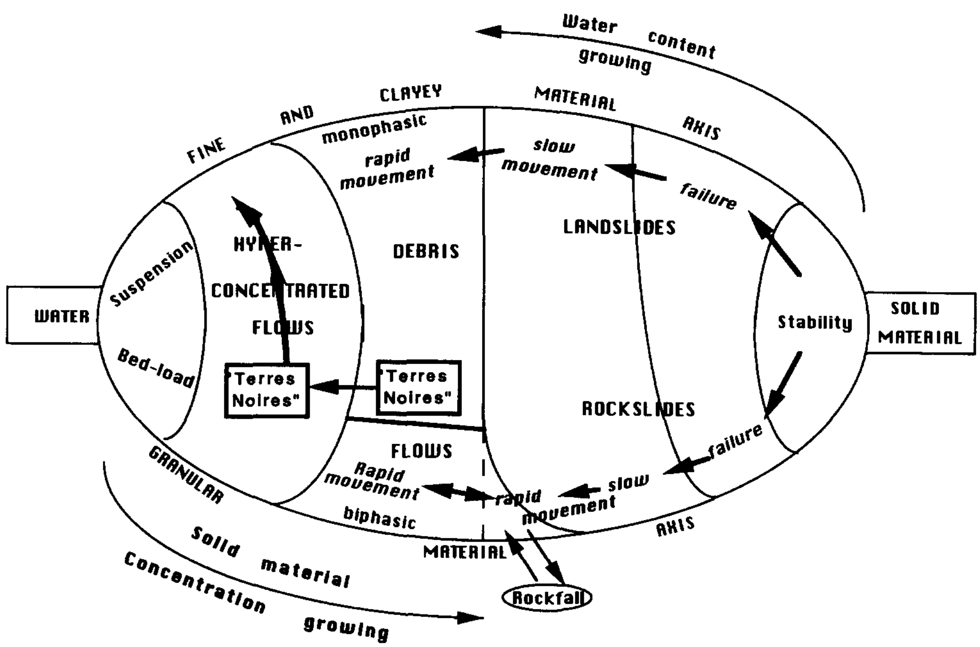

Fig. 7. Variation in the nature of solid transport flow in the "Terres Noires" along the stream profile.

deposited in the sediment traps to the total volume varies from one flood to another. The variation in the average values calculated for a series of events and as a function of the catchment surface area is given in Fig. 6. Note that the decrease is very rapid. For surface areas of over a few km^2, it may be assumed that coarse marly materials are virtually all destroyed, with only stones and gravel from surface formations remaining for bed-load transport. It is, therefore, reasonable to consider only concentrated suspension transport.

6.2. Concentration and nature of fluids

The concentration of transported solids varies considerably from one flood to the next. During high floods experienced in spring, or during summer storms after a long dry period, the solid flow to liquid flow ratio may be as high as 30% (concentration per unit volume[2], $C_v = 0.23$). The measuring system used in Draix does not provide the concentration upstream of the sediment traps. On the other hand, from data obtained downstream of the traps, concentration values of up to 500 g/l ($C_v = 0.19$) were obtained. These values are of the same order of magnitude as those measured on the tributaries of the Yellow River (Wang Mingfu et al., 1985; Wang Zhaoyin and Larsen, 1994b). These flows fall in the category of hyperconcentrated flows (Fig. 7) according to the classification of Meunier (1994), with rapid evolution towards the fine material axis. When the concentration per unit volume exceeds 0.45 to 0.5, the small upstream gullies may also give rise to debris flows that, in the different flow fields of Fig. 7, are situated in the monophasic or muddy debris flow category.

The flows observed in the "Terres Noires" may thus be placed in different categories (Fig. 7), although each category occurs in a different part of the drainage channel: (1) on slopes with gradients from 40 to 70%, many miniature debris flows occur during storms; (2) in the upstream gullies (gradients from 15 to 35%), occasionally muddy debris flows occur, but above all, hyperconcentrated flows of coarse materials; and (3) in

[2]The concentration per unit volume is equal to the solid volume divided by the total volume.

reaches with gradients from 4 to 12%, muddy debris flows occur on rare occasions, but, above all, hyperconcentrated flows of coarse materials, quickly transforming into hyperconcentrated flows with predominantly fine materials.

The types of flows thus change from upstream to downstream in the "Terres Noires". This change, shown on the general diagram of Fig. 7, is typical of such solid material, due to the rapid change from coarse to fine material.

6.3. Rheology

A rheology study of the fine part of the solids from the "Terres Noires" was carried out for extremely concentrated suspensions: $C_v = 0.3$–0.43 (i.e., 795–1140 g/l). The flow curves obtained are shown in Fig. 8. These fluids are non-Newtonian: it is evident that their flow curves fit the Hershell–Bulkley law very well. This law is expressed as follows, in terms of τ (τ = shear stress, du/dy = shear rate):

$$\tau = \tau c + k(du/dy)^{0.333} \quad \text{if } (du/dy) > 0$$
$$\tau < \tau c \quad \text{if } (du/dy) = 0$$

The concentrations of the fine fraction alone correspond to real fluids of higher concentrations ($C_v > 0.45$–0.5), and thus to debris flows.

At very high concentrations, the flows from the "Terres Noires" consist of fluids with an initial yield stress τc which varies exponentially with the value of C_v, as shown in Fig. 9 which is a typical result for muddy suspensions (O'Brien and Julien, 1985; Coussot, 1993).

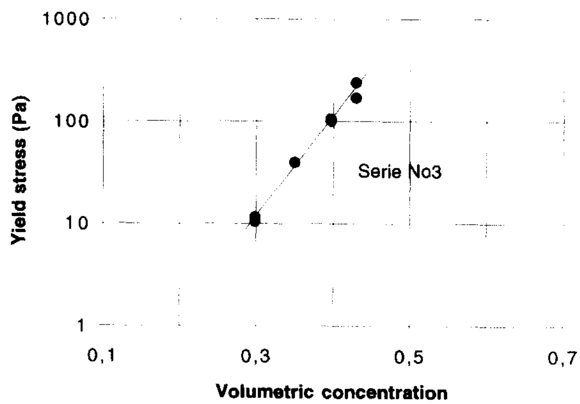

Fig. 9. Yield stress against volumetric concentration for Roubine solid material.

6.4. Hydraulics

Because the flows described above can be placed in three different categories, it is necessary to apply three different hydraulic theories.

6.4.1. Debris flows

The theory especially devised at Cemagref for muddy debris flows (Coussot, 1994) using the Henshell–Bulkley model, is well suited to this category. At these very high concentrations, the

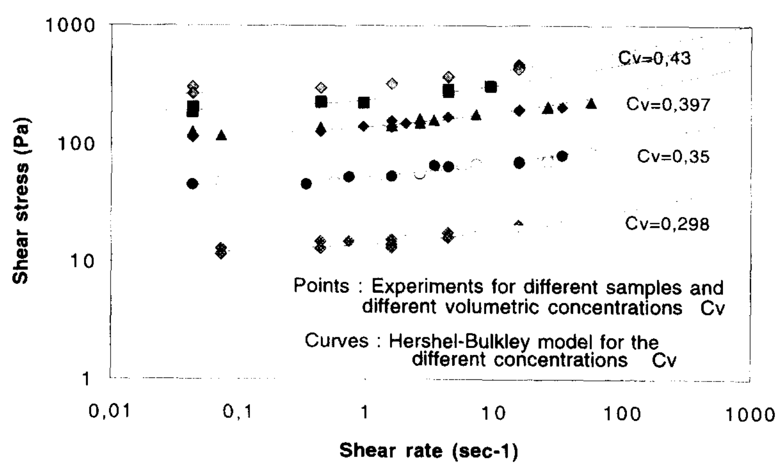

Fig. 8. Concentrated suspension flow curves for Roubine fine material fitted to the Hershell-Bulkley model.

flows are completely laminar. However, it should be noted that the flow front is often made up of blocks of rock and that, up till now, no law has been established to describe their behaviour.

6.4.2. *Hyperconcentrated flows containing coarse materials*

The phenomena of hyperconcentrated flows with coarse debris are very complex and have not been studied in great detail. The law describing the behaviour of such fluids is hypothetical. At the Cemagref, the law applicable to river solid transport was simply extrapolated: (1) the Newtonian approximation was used for the liquid part of the flow; (2) for solid transport, the hyperconcentrated bedload transport formulae were used. These are applicable to steep gradients and were established from laboratory tests. These formulae give satisfactory orders of magnitude for the coarse materials deposited in the sediment traps at Draix (Borges, 1993; Borges et al., 1994). However it should be noted that these results are valid only for small upstream catchment areas and only for coarse sediments.

6.4.3. *Hyperconcentrated flows containing mainly fine materials*

Because coarse materials disintegrate into fines or are deposited, hyperconcentrated flows of fine materials are quickly obtained [concentrations between 100 g/l ($C_v = 0.037$) and 600 g/l ($C_v = 0.23$)]. These flows pose difficult problems because they probably remain non-Newtonian (Wang Zhaoyin et al., 1994a). On the Laval, for example, it was found that, for natural flow downstream of the sediment trap, and for a concentration of 300 g/l ($C_v = 0.11$), the fundamental hydrostatic relationship is not verified (Cambon et al., 1990). From the theoretical standpoint, these fluids create a number of problems which have not yet been properly elucidated: (1) the behaviour law to be used; (2) the transition between low concentration flows and hyperconcentrated flows; (3) the reduction of turbulence by suspended materials and the existence of a maximum suspended material content (Wang Zhaoyin and Larsen, 1994b).

7. Surfacial instabily

The Barcelonnette area (Fig. 1) displays numerous landslides. Some slides are deep-seated, varying in depth from 30 to 60 m. Most were triggered after the final retreat of the glaciers (Legier, 1977). After periods of inactivity, some are reactivated and are presently active (Salomé and Beukenkamp, 1988; Weber, 1994). It is worth noting that the occurrence of deep-seated movements is not very frequent in the "Terres Noires". From this point of view, the Barcelonnette region (Fig. 1) appears to be unique.

The majority of the slides are shallow and are developed in the weathered superficial top soils including morainic slope formations. The maximum thickness of this soil cover ranges between 5 and 10 m, if deposited in depressions by solifluction or ancient mass movement processes. Slides can be triggered in such zones by long periods of rainfall.

7.1. *Geophysical and geotechnical characteristics of the colluvial material derived from "Terres Noires"*

Geophysical methods proved to be helpful to determine the depth of the sound "Terres Noires" substratum beneath the colluvium (and thus the potential depth of a slip surface) and to detect variations in water content. (Caris, 1991). Resistivity borehole logs in the colluvium, performed in the Riou Bourdoux catchment near Barcelonnette, gave values between 30 and 15 ohm m depending on the water content. Deep resistivity soundings revealed a gradual rise in resistivity in the in situ "Terres Noires" over 2 m, rising from 75–80 ohm m to 150 ohm m, indicative of a weathered zone on top of bedrock.

Seismic velocity measurements are a helpful means of describing the base of the top soil due to the excellent contrast in velocity between the soft cover (about 340 m/s) and the bedrock (about 2500–3000 m/s) (Caris, 1991).

An intensive geotechnical investigation was carried out at sites near Barcelonnette and Jausier, in order to estimate strength values for the colluvial "Terres Noires" material. On the basis of 131 drained direct shear tests (sample diameter 63 mm) the mean friction angle is 35.4° (variance 3.8) and mean cohesion is 13.5 kPa (variance 49.1).

Drained triaxial tests on 19 samples (diameter 66 mm) show probably more realistic lower values and higher variances (mean friction angle: 24.7°, var. 0.37; mean cohesion: 12.4 kPa, var. 243.5). No significant differences were found in the mean values of the strength parameters in the root zone. Mulder (1991) explained that roots contribute to the strength of the soil only for shear strains greater than 0.4; conditions which are hardly met during tests on small samples.

7.2. Hydrological characteristics of the weathered "Terres Noires"

Hydrological measurements were carried out at two sites in the Barcelonnette area (near Jausier and in the Riou Bourdoux). Fig. 10 shows values

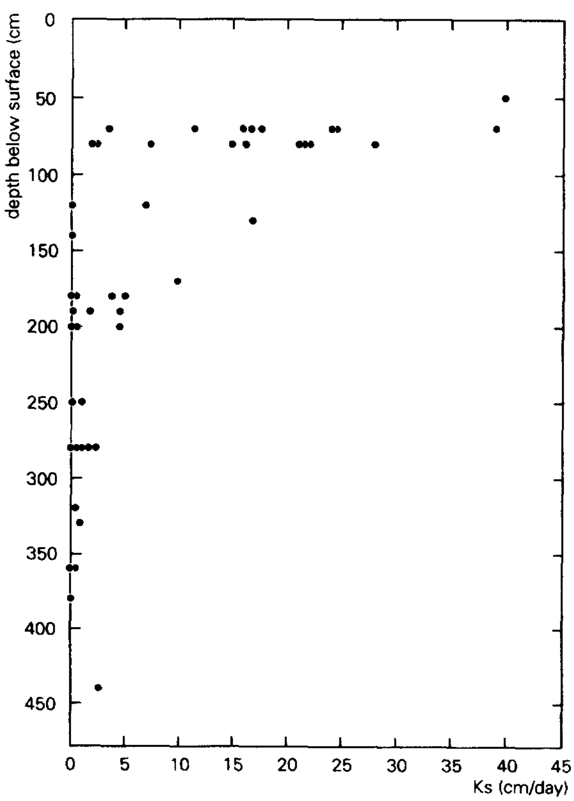

Fig. 10. Variation in saturated hydraulic conductivity with depth for weathered colluvial "Terres Noires" material.

of the saturated hydraulic conductivity measured at different depths, with the inverse borehole method (Oosterwegel and Van Veen, 1988). Two layers can be distinguished in the colluvial material: a relatively permeable top layer (layer 1) with a thickness of 1 to 1.5 m, and a relatively impermeable sublayer (layer 2). The saturated hydraulic conductivity in the top layer varies considerably, ranging from 5 to 40 cm per day. Conductivity values obtained from measurements performed on 25 x 25 x 25 cm soil cubes gave far higher values, ranging from 1.50 to 4 m per day (Caris, 1991). Macropores and fissures play a major role in the permeability of the top layer as evidenced by their higher mean values and variances compared with the sublayer. The colluvial material of layer 2 is relatively impermeable with hydraulic conductivities ranging between 0.05 and 5 cm/day.

Tensiometer measurements at different depths in the colluvium were perfomed with a view to understanding the behaviour of water in layer 1 and the more impermeable colluvial material beneath. The water clearly concentrates in the top layer due to the contrast in hydraulic conductivity between layer 1 and layer 2 (Fig. 10). In fact, the water concentration in the layer 1 controls the flows into layer 2. There are significant temporary moisture fluctuations in the top layer as an immediate response to rainfall and evapotranspiration. Fig. 11 also shows that a short-term increase in the moisture content of layer 1 does not result in a significant downward flow of water. The moisture content (suction) in layer 2 remains fairly constant with time, with a tendency for an increased moisture content (lower suction) with depth. It can, therefore, be imagined that only a perched groundwater table in the top layer over longer periods could supply significant downward flows to the sublayer.

7.3. Meteorological instability conditions for surface landslides in "Terres Noires" weathered material

Generally speaking, the unstable slopes are characterised by shallow slides with a flat slip surface running more or less parallel to the topography at depths varying from 5 to 7 m. The length of the

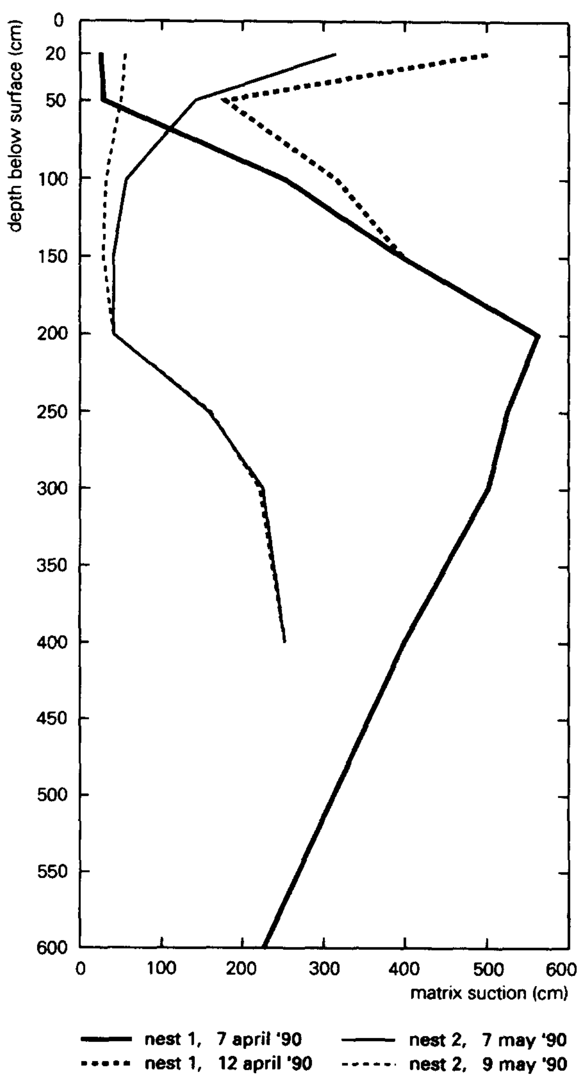

Fig. 11. Time-dependent variation in matrix suction in two profiles in weathered colluvial "Terres Noires".

slides varies from 80 to 120 m. The landslides can be reactivated in a particular year, separated by inactive periods ranging from 5 to 12 years. This could be detected by dendrochronological research on bent tree stems over a maximum period of 100 years BP (Van Asch and Van Steijn, 1991; Van Asch, 1995). Ground water modelling on a monthly basis over 25 years, using the two-layer concept described above, shows a yearly fluctuation in the phreatic water table in the colluvial material of layer 2, with peaks at the end of the winter period and at the beginning of spring, and minimum values during the dry summer period. The hydrological monitoring presented above already suggested that long periods of rainfall are needed to create a permanent perched water table in the top layer in order to induce significant flows to the sublayer.

The hydrological investigations and modelling of failure conditions in layer 1 and layer 2 of colluvial material indicate that the installation of interception drains in the 1.5-m-thick permeable upper layer of the landslide should probably constitute an effective measure for stabilisation of these superficial slides in the colluvial material.

8. Conclusions

The "Terres Noires", which cover large areas of southeastern France, consist of easily weathered and erodable materials. This susceptibility to weathering makes them particularly prone to erosion, leading to high levels of solid transport, contributing to the alluviation of man-made reservoirs. In addition, these formations are affected by surface instabilities.

The majority of the slides are shallow and are developed in the near-surface weathered colluvial soils.

Plant cover plays a fundamental role in the protection of these formations against surface erosion. For example, in a catchment area with a dense plant cover, denuded areas are not only small in size, or non-existent, but even where they do occur, the rate of erosion may be as much as 50 times lower than on equivalent surfaces in a catchment area without plant cover. References not cited in the text Hazeu, 1988, Kruse and Terlien, 1990

Acknowledgment

We would like to thank Mr Cambon, Mr Olivier and Mrs Mathys from Cemagref for the supply of quantitative data on Draix ERB. The authors would also like to thank Prof. John Hutchinson of Imperial College, London, for the assistance he gave in finalising this article.

References

Artru, P., 1972. Les "Terres Noires" du bassin rhodanien: stratigraphie, sédimentologie, géochimie. Thèse docteur ès-sciences. Univ. Claude Bernard, Lyon, 178 pp.

Borges, A.L., Brochot, S. and Meunier, M., 1994. Modèle hydrosédimentologique des écoulements hyperconcentrés d'un petit torrent des Alpes du Sud. La Houille Blanche, 3/94: 71–80.

Borges, A.L., 1993. Modélisation de l'érosion sur deux bassins versants expérimentaux des Alpes du Sud. Cemagref. Thèse de l'Université Joseph Fourier. Grenoble, 205 pp.

Cambon, J.P., Mathys, N., Meunier, M. and Olivier, J.O., 1990. Mesures des débits solides et liquides sur des bassins versants de montagne. Symp. Hydrology in Mountainous Regions, Lausanne. AIHS Publ., 194: 231–238.

Caris, J. and Van Asch Th.W.J., 1991. Geophysical, geotechnical and hydrological investigations of a small landslide in the French Alps. Eng. Geol., 31: 249–276.

Coussot, P., 1993. Rhéologie des Boues et Laves Torrentielles. Etude de Dispersions et Suspensions Concentrées. Thèse Inst. National Polytechnique de Grenoble. Laboratoire de Rhéologie, Cemagref Série Etudes Montagne, 5, 416 pp.

Coussot, P., 1994. Steady, laminar flow of concentrated mud suspensions in open channel. J. Hydraul. Res., 32(4): 535–559.

Descroix, L., 1985. Contribution à l'étude de la dynamique érosive dans les Baronnies orientales et les pays du Buech moyen. Problèmes d'aménagement. Thèse de doctorat de troisième cycle de géographie de l'aménagement. Lyon II, 260 pp.

Dumollard, B., 1984. Mise au point d'une technique d'étude et de mesure de l'altération des marnes dans les "Terres Noires". Rapp. ISTG, Cemagref, Grenoble, 63 pp.

Hazeu, G.W., 1988. Grondmechanische proeven op morene materiaal. M.Sc. thesis, Dep. Physical Geography, Univ. Utrecht, 44 pp.

Kruse, H. and Terlien, M., 1990. Een model voor temporele analyse van massabewegingen. M.Sc. thesis, Dep. Physical Geography, Univ. Utrecht, 77 pp.

Legier, A., 1977. Mouvements de terrain et évolution récente du relief dans la région de Barcelonnette (Alpes-de-Haute-Provence). Thèse, Université de Grenoble, 163 pp.

Mulder, H.F.H.M., 1991. Assessment of landslide hazards. Thesis Faculteit Ruimtelijke Wetenschappen, Nederlandse Geografische Studies, 124, Utrecht, 150 pp.

Mahmood, K., 1987. Reservoir Sedimentation. Impact, Extent and Mitigation. World Bank Tech. Pap., 71, 118 pp.

Mathys, N. and Meunier, M., 1989. Mesure et interprétation du processus d'érosion dans les marnes des Alpes du Sud à l'échelle de la petite ravine. Colloque transport solide, Nov. 88. SHF Paris, La Houille Blanche, 1989(3/4): 188–192.

Meunier, M., 1994. Les progrès de la connaissance et les méthodes d'étude des phénomènes torrentiels. La Houille Blanche, 1994(3): 25–31.

O'Brien, J.S. and Julien, P.Y., 1985. Physical properties and mechanics of hyperconcentrated sediment flows. Proc. Specialty Conf. Delineation of Landslides, Flash Floods and Debris Flow Hazards in Utah. Logan Utah, June 1984, pp. 260–279.

Oostwoud Wijdenes, D. and Ergenzinger, P., 1995. Erosion and sediment transport under simulated rainfall on steep marly hillslopes, Draix, Haute-Provence. C. R. Rech., 3. Bassins Versants Experimentaux de Draix. Collection Études. Série Équipements pour l'Eau et l'Environnement. Cemagref Éditions.

Oosterwegel, J.L.V. and Van Veen, E.W.H., 1988. Grondwaterstroming op instabiele hellingen. M.Sc. thesis, Dep. Physical Geography, Univ. Utrecht, 72 pp.

Phan Thi San Ha, 1992. Propriétés physiques et caractéristiques géotechniques des "Terres Noires" du sud-est de la France. Thèse Univ. Joseph Fourier, Grenoble, 246 pp.

Salomé, A.I. and Beukenkamp, P.C., 1988. Geomorphological mapping of a high-mountain area, in black and white. Z. Geomor., 33(1): 119–123.

Van Asch, Th.W.J., 1995. Modelling ground water fluctuations and the frequency of movement of a landslide in the Terres Noires region of Barcelonnette (France). Earth Surface Process. Landforms.

Van Asch, Th.W.J. and Van Steijn, H., 1991. Temporal patterns of mass movements in the French Alps, Catena. 18: 515–527.

Walling, D.E., 1988. Measuring sediment yield from river basins. In: R. Lal (Editor), Soil Erosion Research Methods. Soil Water Conserv. Soc., Iowa, pp. 39–73.

Wang Mingfu, Duan Wenzhong, Tan Guangming and Zhan Yizheng, 1985. On the structure and movement mechanism of flow with hyperconcentration of sediment. Int. Workshop Flow at Hyperconcentrations of Sediment. Beijing, II3-1–II3-19.

Wang Zhaoyin, Larsen, P. and Wei Xiang, 1994a. Rheological properties of sediment suspensions and their implications. J. Hydraul. Res., 32(4): 495–516.

Wang Zhaoyin and Larsen, P., 1994b. Turbulent structure of water and clay suspensions with bed load. J. Hydraul. Eng., 120(5): 577–600.

Weber, D., 1994. Research into earth movements in the Barcelonnette basin. In: Temporal Occurrence and Forecasting of Landslides in the European Community. EC Final Rep., II(1): 321–336.