Geotechnical investigations into the Super Sauze landslide. Geomorphological and hydrogeological results.

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OBJECTIVE

General objective: On-site investigation into the internal characteristics of marl rock landslides, upstream, downstream and from the surface downward, including locating breaks at various levels and examining the physical characteristics of the material between them, to assist in the choice and application of behaviour models.

1. THE MAIN FORMATIONS

Material can be observed in the ablation and accumulation zones and on the surface by means of the gullies which cut through the body of the flow. Moving from the depths to the surface three main formations can be distinguished.

1.1. Marl.

It reinforces the main escarpment and the flanks of high, steep-sided gullies. They also occur in the accumulation zone at two main locations, over the length of profile B (fig. 1), which comprises two old gullies spars partially covered by the flow material. This marl is a compact and resistant formation, with facies of black clay shale. The schistosity cuts the massif into small beds, flakes or irregular slabs of from around 1 to 3 cm. thick. Fracture planes and sedimentary structures can also be seen here throughout the length of the gullies but particularly on the main 'restored' escarpment; they are often outlined by a bed of calcite. These fracture planes cut the massif into fairly voluminous blocks with grooving.

1.2. Disintegrating slabs and blocks of marl.

They vary in size from a few cubic metres to several tens of metres and can be seen mainly in the ablation zone at the floor of the main escarpment on the gently sloping upper shoulder, between altitudes of approx. 1940-1960 m. They constitute a really chaotic field over which it is difficult to progress. These sharply ridged blocks of marl project sharply upstream, but with distance the ridges become weathered and the blocks smoother and rounder, barely emerging from the accumulation formation. Progressively, then, we pass from a field of dislocated and disintegrating blocks to an uneven surface with crumbling blocks and finally to a slightly uneven surface scattered with calcite and moraine pebbles, weathered stones and flakes of all sizes. Blocks of marl, still solid and with the schistosity plane clearly visible just below the surface or buried several metres deep in a heterogenous clay matrix may be observed by way of interconnected gullies, and particularly the main gully, which cuts into the accumulation zone to a depth of several metres at an altitude of approx. 1800-1900 m.

1.3. The heterogenous marl-clay formation.

This is a very heterogenous formation with a matrix of fairly fine clay containing rounded pebbles and flakes (2 or 3 cm long and less than a centimetre thick) and small flat flakes of debris which crumble in the fingers. This formation surrounds the marls blocks described above. In well-watered zones it becomes liquid mud and it is dangerous to venture onto it.

1.4. Other formations can be seen, but they are smaller and less numerous. They include the moraine formation, several metres thick, visible on the upper part of the main escarpment; the surface of the landslide flow is strewn with chalk blocks of sizes varying from a few decimetres to several cubic metres, particularly over the upper third of the escarpment. Alluvial deposits and boulders are also present at the foot of the main escarpment in the form aprons, debris cones and spreads. The base of the gully flanks are also covered with alluvium (blocks of all sizes).

It is immediately evident, before any closer investigation, that the accumulation zone consists of a very heterogenous fine plastic formation containing unstable blocks and slabs, from upstream to downstream and from the surface to the depths, with narrower mudflows. These observations give rise to many questions regarding the thickness of these formations which cover a paleotopography. Depending on its position and direction, this paleotopography must have a significant effect on possible divisions in the mass moving between wholly- or partly-covered gullies, on the thickness of this accumulated mass and on the canalisation, the dispersal or the concentration of water.

1.5. Questions raised by these observations.

1. What is the geometry (shape, dimensions, depth) of the gully(s) covered by moving material ?
2. Are there two independent vertical structures inside the accumulation formation ?
3. If so, what is the thickness of the first structure, possibly viscous and restricted, extending laterally *(continuous medium mechanics)*, and developing seasonally, depending on its degree of saturation ?
4. Is the second structure also viscous or plastic/rigid *(solids mechanics*) Is it limited by a well-defined sliding surface or by a transition zone ?.
5. Or does the moving mass flow continually throughout its thickness?
6. What are the intrinsic characteristics of these various layers - viscosity, resistance to immediate or residual shearing?
7. What is the permeability of the moving mass overall? Do the numerous vertical surface cracks give rise to a very permeable first layer, rapidly saturated, then to a second, the permeability of which allows the formation of a continuous level, free or otherwise, which will increase with the inflow and cause harmful interstitial pressure?.
8 Or is it a compact mass, as appears to be the case at La Valette, as impermeable as or more impermeable than the marls themselves, not flowing and behaving like a rigid mass?.

2. GEOTECHNICAL INVESTIGATIONS

2.1. Methods used.

Access is difficult because of wet and muddy zones and large, deep gullies. Because of this we chose « light » investigative tools and techniques, supplemented by « heavier » tools, to install inclinometric tubes and open piezometers and to carry out pressiometric trials and water tests (Lugeon and Lefranc).

- A powerful, high-performance **NUZI** 100 ch drill allowing for all types of investigation; however, its weight and limited mobility on a scarped terrain required expensive helicopter transport. Because of the limited budget INFRASOL were only able to use this machine for six deep drillings spread over two distinct zones.

- A DL 030 heavy **dynamic penetrometer** with a 30 kg monkey and a light dynamic penetrometer with a 10 kg monkey.

- A **percussion drill** with bits 30 to 100 mm in diameter which allowed us to look at the nature of the soil and to take intact or reworked samples to a depth of around 8 m.

The general principle was to grade and correlate the results obtained by various methods at several points and then to extend the investigation using more manoeuvrable tools such as dynamic penetrometers and a percussion drill.

2.2. Geophysical investigation.

A geophysical reconnaissance was carried out by seismic refraction and electrical prospection in October 1995 in collaboration with the E.O.P.G. in Strasbourg (Ecole et Observatoire de Physique du Globe - Global Physics School and Observatory). It included :

- 5 electrical trackings
- 11 electrical drillings
- 16 seismic drillings with 50-mm flûtes and inverse and direct shots.

The sites of the various investigation points are set out in figure n° 2, together with the main results.

2.2.1. Seismic.

The results were interpreted after filtering and spectral analysis of the noise and the signal. We were able to demonstrate three distinct media:

- **a considerably degenerated medium at a low speed** (between 400 and 700 m/s), which was found over all the drillings. Two types of speed are visible. The first oscillates around 450-500 m/s for thicknesses of 2.5 to 5 metres and the second around 750 m/s for thicknesses of from 6.5 to 8.5 metres.

- **an intermediate layer at a slightly higher speed** (between 1000 and 1600 m/s) which occurred in only a few drillings. The thickness calculated only on profiles L1 and L2 on the higher part of the landslide are between 17 and 20 metres.

- **The substratum** (the marl in situ) which has not reached speeds of around 2000 and 3200 m/s in any of these drillings.

2.2.2. Electrical.

Two interpretation methods were used, the first being RESIST for resistivity (the normal method designed by Vander Velpen) and second being the Bayes method (carried out by J-J Schott/EOPG de Strasbourg). The general principles and the main results are as follows:

RESIST: This mathematically-based method requires the number of layers to be fixed in advance in accordance with the apparent resistivity values observed. Thickness and resistivity measurements must be given for the layers as a departure point for the model, bearing in mind that they will be changed during modelling. The final curve is a function of the values observed and the number of layers fixed.

Bayes Analysis: This new, statistically based method enables us to find the most probable resistivity value for each layer, given that the soil comprises a very large number of theoretical layers. These layers have no physical existence and only serve to subdivide the soil. This theory derives from Bayes theorem for calculating probabilities when all the information concerning a series of events is not available.

In the RESIST determinist method the substratum of the model, which comprises 3 to 5 layers, is represented by the base of the conducting layer. This substratum is located at depths of 2.5 to 6.4 m.

With multi-layer Bayes analyses in models with two units (each corresponding to a layer of the landslide resting on the substratum), the thicknesses of the first unit are between 4 m and 1 m. The thicknesses of the second unit are between 20 m and 7 m.

RESIST interpretations (alone and with Bayes) are much less detailed than the BAYES interpretation. It seems that the substratum and the last conducting layer detected by Bayes are transformed into a single intermediary layer with RESIST. Furthermore, in the case of depths, if we multiply the thickness / resistivity ratio factors by 2 we reach the same results as by the Bayes analysis. This is quite plausible given the uncertainty attached to the RESIST models. RESIST and Bayes are therefore rendered compatible.

2.3. Drillings and ponctuels instruments.

2.3.1. Types of drilling carried out.

- **a core sampling bore**, 116 mm in diameter over a length of 13.50 m.

- **Five destructive borings** (tricone rock bit), diameter 63 mm or 100 mm with recording of parameters (advance speed, pressure on the tool, injection pressure) to a depth varying between 18.50 ml to 28.80 ml (total 118 ml).

- **One hundred one drilling with light and heavy dynamic penetrometer** to measure the resistances of the rod (Qd) and to verify the homogeniety of the soil in depth.

- **Thirteen percussion drillings** to check the nature of the soil and to take intact or reworked samples to a depth carying between 0.70 ml and 7.00 ml (total 49 ml).

- **Ten pressiometric tests** to measure the geomechanical characteristics of the soil in situ (pressiometric module (E), flow pressure (Pf) and pressure limit (Pl)).

- **Thirty-two open piezometers** diameter 25 mm (19), 40 mm (30) and 50 mm (10) cstrainers at different depths and over variable lengths (Cf description of each piezometer), with gravel filter (0.03 / 0.06) or filtering sock and bentonite stopper (ring approx. 20 to 30 cm. high)
- **Three inclinometric tubes** to detect the depth of the rupture surface(s) and to measure the movements

- **A Lugeon type permeability test** in the marl in situ

- **Ten lefranc type permeability tests** (drainage and measurement of the rise in terms of time)

- **Eight double ring infiltrometer tests**

2.3.2. Operating modes and interpretation of results.

* Installation of investigations

As shown in fig. 1, most of the drillings were spread over five transverse transects, themselves distributed from the upper shelf (altitude around 1950 m.), dominated by the main ledge, to the lower shelf (altitude around 1800 m.), about a hundred metres from the foot of the flow. They are situated not far from the topometric marker lines (Cf earlier). They enable us to line up the transverse cuts with the landslide-mudflow.

Zone	Dynamic Penetrometer	Percussion drilling	Destructive & parameter boring	Core sampling bore	Piezometer	Inclinometer	Pressiometer
A	14		2	1	1	2	11
B	26	6			8		3
C	26	3	3		10	1	
D	16	2			3		
E	19	2			10		
Total	**101**	**13**	**5**	**1**	**32**	**3**	**14**

* Dynamic penetration testing principle

This test comprises driving a conical test wedge into the soil under known conditions (weight of monkey, rods, height of fall). We measure the depth for each drop of the monkey or for a fall of 10 cm.

The machines used are heavy and light penetrometers (30 kg monkey and 10 kg monkey) with a 35 mm probe tip. The rod diameter is only is 22 mm, in order to avoid lateral rubbing over the length of the wall of the hole. We use the « Dutch » formula to determine the soil's resistance to the penetrometer probe tip.

$$Qd = \frac{M^2 \times H}{(M + Ct)} \cdot \frac{1}{S} \cdot \frac{N}{e}$$

Qd = resistance of the rod 10^5 Pa or bar
M = weight of monkey in kg (30 kg or 10 kg)
H = height of fall in cm (20 cm or 50 cm)
Ct = weight of penetrometer (body of machine and rods)
S = Section of probe tip (10 cm^2)
N = number of monkey drops corresponding to drive, e
e = drive in cm. (10 cm)
The results are presented in the form of a pentogram on which the resistance of the rod Qd in Mpa (abscissa) is given as a function of the depth (ordinate). The characteristics of the penetrometer used are also indicated on this graph Fig. 4 to 7).

This test is easily mounted, quick and cheap. Because of the low weight of the equipment (a mere 200 kg !) we were able to use it in areas which were inaccessible for other tests requiring heavier equipment. Nevertheless it was inconvenient in some respects.

The machinery we used (DL030 with 30-kg monkey) obliged us to limit our investigations to depths below 10 m, mainly because of lateral rubbing which might develop in the passing through unstable layers. In the same way the presence of numerous blocks of moraine or areas of fairly solid marl was a major inconvenience, as the probe couldn't penetrate this very resistant material. When stones or pebbles were buried in a less resistant mass the probe could chase them; this appears on the curves as a succession of very localised peaks (Fig. 4 & 5). In the marl in situ or on a slab of marl buried in the mud flow over a thickness of several decimetres the resistance increases progressively, reaching figures of 25 Mpa or more, i.e. more than 100 drops to sink the 10 cm probe (Fig. 6). Sometimes we were able to drill through a thin resistant layer by forcing the drive and to continue drilling through a less resistant layer (Fig. 7). This example clearly illustrates the major problem of « pseudo-blockage » which could have been partly solved by using a more powerful machine (a heavier monkey and a higher drop); however, this would have created other problems (movement, weight etc.).

Interpretation is difficult, as it is a 'blind' test. It should be used very carefully in stable saturated soils and in fine submerged soils. For these reasons several gaugings were carried out with pressiometric tests and destructive samplings whose parameters were recorded.

* Pressiometric testing principle

The pressiometric test is a static loading of the soil. It consists in sinking an inflatable cylindrical probe through a carefully calibrated drill (Fig.8a). The volume variations in the ground in contact with the drill are measured in terms of the pressure applied. We obtain a ground constraint-deformation curve in the hypothesis of a deformation plane (Fig.8b). Three ground characteristics can be deduced:

- **the pressiometric module E** which defines the pseudo-elastic behaviour of the ground,
- **the flow pressure Pf** which defines the limit between the pseudo-elastic behaviour and the plastic phase,
- **Pressure limit P1** which defines the ground's resistance to rupture.

The pressiometric characteristics obtained for the various layers drilled enable us to arrive at other unmeasured characteristics by correlation; these include the Young module, viscosity, based on various studies carried out elsewhere.

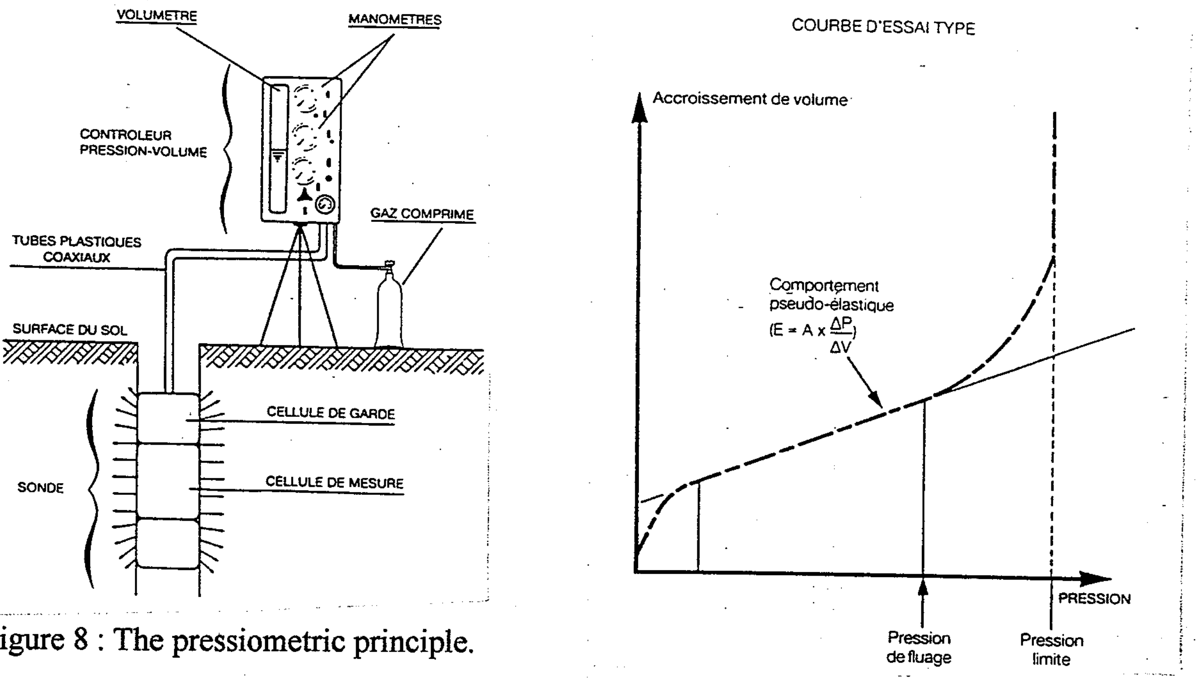

Figure 8 : The pressiometric principle.

3. GEOMORPHOLOGICAL AND HYDROGEOLOGICAL RESULTS.

3.1. Geometric and geomecha~~n~~mical features.

Geotechnical prospection commenced in May 1996 and continued throughout the summer until 20 September, so many tests have only been partially interpreted and the laboratory tests have not yet been carried out. This being so, we can only give the main and most obvious results, specifying as far as possible which analyses are yet to be made. Answers to the questions set out earlier are still incomplete.

If we simplify the results already obtained we can distinguish three main layers with the following characteristics:

N°	Nature	Qd (Mpa) (Fig 6)	Pl (Mpa) (Fig. 9)	Speed of advance (m/s) (Fig. 10 et 11)
1a	Very soft wet mud	< 1	not measurable	> 125
1b	Soft wet mud	<3	< 0.3	
2	Clay hard consistancy	3 à 8-10	1.35 < Pl < 0.3	10 à 125
3	Compact clay or marl in situ	> 8 blockage	Pl > 1.35	< 10

Layer 1: This layer, on the surface or under a layer of approx. 10-30 cm. varies in thickness from 2 - 3 m. to more than 7 m. Except in special cases where a pseudo-blockage has been recorded, we can state that the thickness of this layer is correctly defined overall. It is a reworked and fairly heterogenous marl formation with a fine, damp matrix. A few small blocks of marl in an advanced stage of deteriation are buried in it. They show on the penetrograms as small peaks of local resistance.

In very wet zones we can distinguish a sub-category for which there is almost no resistance of the rod, the weight of the rods being sufficient for penetration. This is liquid mud.

Layer 2: This second layer is heterogenous and shows many resistance peaks. It, too, is made up of reworked marl, but deterioration is less advanced and it is drier and more compact than the first layer. It contains many blocks of marl, stable but deteriorating. There are a few small layers, very thin, and small flows occur in them. The thickness of this layer is very variable.

Layer 3 This is a stiff, compact formation, consisting of marl either in solid blocks or with a slightly eroded surface. The penetromer was blocked fairly quickly in this formation. This layer is only formally identified in a few drillings because of many early blockages over a block of moraine or calcite.

In conclusion, we can state that the formation of accumulation comprises two superimposed layers, the first being very wet viscous mud and the second rigid/plastic, more stable and more compact. Furthermore, as observed previously, these two distinct layers contain marl blocks of various sizes, their degree of instability being more advanced downstream. We can offer an indirect explanation for this. It is important to note that, overall, the penetrometer drillings carried out in the lower part of the mudflow, starting at profile D (Fig. 1) reach greater depths than those carried out upstream. Pseudo-blockages and localised resistance peaks within a single layer are more numerous, as in the upper part of profile A, for example. This arises partly because there are fewer moraine blocks and partly because of greater instability in the marl blocks in the reworked formation.

3.2. Paleotopography.

In spite of earlier observations regarding the risk of errors in the localisation of the top walls of the marl in situ we have managed to trace the paleotopography for all doubtful sectors on our various transverse profiles, either as a continuous line or as a dotted line (Fig. 12).

The risk of errors is smallest for profiles B and D, the fact that there are still a few sectors to be specified later, by a few additional drillings, or by results obtained by photo-restitution.

3.3. Hydrogeology and flows.

3.3.1. Deep flows : layer or not?

Water inflows were observed during the drillings at different depths at almost all sinkings. The levels were followed up at the time in relation to the climatic conditions using open piezometric tubes pierced at different depths. For the moment measurements are only taken from time to time but we intend to install two continuous measurement captors. Using these level measurements and the pemeability tests designed by Lefranc and Lugeon we will in future be able to confirm the existene of the following:

- **a more or less continuous subsurface circulation** with piezometric levels between 0.50 and 1.50 from the topographic surface. These levels fluctuate fairly slowly by a few centimetres a day, with pluviometric response times of several hours. Lefranc tests for drainage show low permeability of the order of 10 -6 m/s. This longitudinal circulation is partly channelled by the paleotopographyn clearly visible in the profile B sector. The deepest gullies collect this water , lowering the lever of the « table » (acting as a drain). This drainage is particularly easy to see in dry periods.

- a discontinuous circulation level at the depths within the compact reworked layer or at the interface with the first layer. In three of our piezometers this level is 3 - 4 m. from the surface and the pulsations seem very feeble.

- an impermeable marl in situ, without any inflow of water during sinkings. The trench dug along the spur of the gully and located on profile B shows the reworked, muddy (and therefore very wet) formation flowing over the very dry marl. The Lugeon test by injection under pressure shows very low permeability, less than 10^{-8} m/s approx.

3.3.2. Surface flows

The surface drainage axes comprise, firstly, the gullies and the intra-flowing gullies and secondly by mixed flow-marl gullies in situ which have cut into the banks of the flow. The first type have an intermittent flow directly related to rainfall episodes, particularly during storms (taken up and dried out rapidly). The second are perennial, though the flow varies greatly with the season and the pluviometric conditions.

Their role is significant in several respects both in drainage, as noted earlier, and more particularly in their erosive action. The latter carries a solid and appreciable load mainly during flooding, with two possible consequences: the first in terms of the balance between the quantity of incoming and outgoing material (supplied from the main ledge), the second in terms of maintaining the instability, in particular on the western edge of the flow.