Stages in the development of the Super Sauze landslide.

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1. BRIEF INTRODUCTION TO THE SITE

The Super-Sauze winter sports station is situated 5 km. from Barcelonnette on the Enchastrayes commune's land in the Restefond massif on the south slope of the Ubaye valley (see general map of the basin included in previous paper). The landslide studied is located in the "Roubines" area, a 75 hectare stretch of bad-land at the foot of the region's two main summits, the Chapeau de Gendarme (2,685 m) and the Brec Second (2,596 m). The geological context in which this bad-land developed consists of black marls of the Callovo-Oxfordian layer.

The crown, certainly the most spectacular geomorphological feature in the landscape of this slope stands out between 1970 and 2150 m. high in a predominantly North-South direction (Figure n°1). The Sauze torrent rises at an altitude of 2070 m. at a place called "La Goutta", only a few meters behind the edge of the crown, at the base of the rock glacier, which is recognizable by its characteristic crescent shape. The main escarpment cuts into the moraine coverage (some ten meters thick) and the subjacent "in situ" black marls steep slopes of 100 meters high on average, corresponding to declivities of around 60°. Two very visible elements demonstrate this geological discord on the terrain : on the one hand, the light beige colour of the moraine material contrasts with the blackness of the marls. Secondly, a very marked break in the slope demonstrates the differently-balanced positions of two formations of different textures and degrees of granulometry. This superimposition also creates a plane of discontinuity from a hydrological viewpoint. Immediately below this main escarpement the so-called "upper shelf" presents the appearance of a slightly rotational sliding mass. The reworked black marls, which include moraine blocks, then turn into a flow over a distance of almost 500 meters. The intermediate slopes on this section are some 20 to 25°. The relatively rectilinear profile is interrupted downstream by a slight convexity, labelled the "lower shelf". Finally the toe of the moving mass is situated at an altitude of 1743 metres, some 820 metres from the farthest point of the crown. In the upper part the flow is almost 200 m. wide, whilst the terminal fold narrows down to only ten metres or so.

2. STUDY OF AERIAL PHOTOGRAPHS

2.1. Methodology.

Because of its location in a grazing zone which is free of anthropic installations, the Super-Sauze landslide is rarely mentioned in the newspapers or in the administrative records. When the Sauze ravine or torrent are mentioned it is in the context of flooding and its consequences, so it is hardly possible to reconstrut the development of this landslide from written or oral testimony.

Given the newness of the shapes observed on the site, this earth movement may be regarded as recent. The I.G.N.'s aerial photography missions over the region during recent decades show us the origins of the phenomenon and enable us to follow some stages of its development. The first mission was in 1948, and there were further flights in 1956, 1971, 1978, 1982 and 1995. Colour Photographs taken in some intervening flights have not been used at present.
The interpretive analysis of these photographs reveals two major facts about the development of this movement:
- the progressive spatial extension of a flow which spreads little by little and « fills » the initial talweg shaped as a "goose-foot" network of ravines.
- sudden mass movements which affect the crown, the repeated withdrawals of which feed material to the body of the landslide.

The successive DEM (Digital Elevation Model) of the unstable sector are carried out in collaboration with the SERTIT (Service Régional de Traitement d'Image et Télédétection) of Strasbourg, using the pictures available. These operations give a three-dimensional picture of the landslide and a calculation of volume variations over the various phases of its development. They provide data concerning the thickness of accumulated material in various sectors of the landslide and this will be validated by drillings and soundings on site.

2.2. Results.

Figure n°2 shows the development of the Super-Sauze landslide over almost half a century in a few simple diagrams.

- In **1948**, over an area of some 75 hectares the site consisted of a network of gullies organised in "goose-foot", forming a bad-land in the black marls. In the upper parts this gully erosion cut into the moraine covering which carpted the old glacial valley between the Brec Second and the Chapeau de Gendarme.

- In **1956**, the landslide had not happened but the morphological clues indicated that it was in preparation. Some grooving in the moraine material gave rise to a circular shape which foreshadowed the present main crown further down the rock glacier. A small flow had already appeared between two ravine crests west of the present landslide.

- In **1971**, there was undeniable movement of material in the upper part, causing a first filling up of the gullies' bottom in the axis of the main talweg ; but most of the trees and the isolated rocks were still visible at this time.

- Between 1971 and **1978**, there were clear and noticeable movements:
- an amphitheatre (formed by sliding or rockfalls) was clearly visible near La Goutta, the east wall of which was the steepest. The footpath passing through this zone and running westward along the base of the Chapeau de Gendarme was cut.
- Another sector of the crown broke away, giving rise to an accumulation of material further down. This accumulation had already begun to develop into a flow.
- the roubine way was established, crossing the Sauze ravine at the level of these gullies, linking the Super-Sauze station with the Gaudessard sector to the west.

- In **1982**, the landslide was almost its present shape. The crown grew larger in the northern part over 4 years. Two accumulation zones were generated by two significant mass movements. Downstream these were mudflows, which caused a progressive filling-up of the initial profile. At that time the downstream limit of the landslide was above what is now the lower ledge: lower down the trees were still clearly identifiable at the bottom of the talweg.

- In **1988**, six years later, while the crown did not fall back significantly, the toe of the slide advanced of about 180 meters, reaching more or less its present position. But the thickness of the material seems to be relatively small.

- In **1995**, the lengthening of the flow continued, but it is not possible de measure on the photographs the precise progression of the base of the foot during this last period. it swept in the very narrow bed cut between the marls of the ravines to the west and the moraine to the east of the flow. This tongue of moraine, partially obstructing the initial talweg, is a sizeable natural obstacle to the flow. Its advance was blocked and it increased the thickness in the lower section. No major movement has been detected around the crown in recent years.

Observations made between the last two photographic missions in 1988 and 1995 can also be confirmed in detail and completed by topometric measurements carried out on site since 1991. This aspect is covered in detail in the third part of this paper.

3. MEASUREMENT OF MOVEMENTS SINCE 1991

The Super-Sauze landslide has been monitored for topometric survey since 1991. The surveillance network for surface movement measurements initially comprised some 40 points taken from two stations : 15 points were placed on the body of the landslide, with 14 more along the crown, 4 on a small unstable zone at some distance from the main movement and the last 7 in various neighbouring sectors, some of which could serve as stable reference points. Ten of the 15 markers initially placed on the body have disappeared during these five years. Most have been replaced by new markers installed nearby. The site of the Super-Sauze landslide is at a relatively high altitude and therefore snowbound for a long time, so campaigns to measure displacements are usually possible only between May and November

A second generation surveillance network came into operation in the summer of 1996. It supplements and improves from a technical point of view the previous network.

3.1. A brief description of the present surveillance network.

The second generation topometric network was installed at the Super-Sauze site in the summer of 1996 and the first measurement campaign was carried out at the beginning of July. The main innovation lies in the construction of two measurement stations in the form of concrete ausculation pillars with a drilled plate which centers the theodolite. The main advantage of these installations is an increase in the precision of the measurements. There are two main reasons for this:
- the centring plates guarantee fully identical three-dimensional placing at these stations throughout all the various measurement campaigns.
- during a measurement recording session over the whole network (which takes several hours) the concrete pillars ensure that the apparatus remains stable - this was much more difficult with the tripod which was used previously.

There are now 67 points on this network (Figure n° 3). Some 50 are distributed over the body and edges of the landslide and there are 15 or so around the edge of the crown. Most of the markers have been installed in accordance with transects close to those retained for the geotechnical investigations. With the exception of two or three which are only visible from one station or the other, all the markers can be sighted successively from each of the two pillars, so we can calculate a position at X, Y and Z, by crossing the informations : we determine the most probable position by the "lower squares" method. Depending on visibility and meteorological conditions each point measured is sighted twice or even three times. At the beginning of September 1996 a series of 5 consecutive measurement recording sessions were carried out in 10 days to detect possible daily movements.

3.2. Main Results.

Twenty measurement campaigns have been carried out on the Super-Sauze landslide between August 1991 and September 1996. Those carried out during the summer of 1996 on the new network are still being processed and the results presented here do not take account of them. Surface movements measured confirm and augment data obtained by comparative interpretation of photographs taken in 1988 and 1995.

Movements are analysed spatially and temporally using graphics showing cumulative horizontal movements in terms of time, or by average speeds calculated according to the time elapsed between two successive topometric readings. Such curves have been established for the mobile reference points which are the most characteristic of the landslide.

Figure n° 4 is a simplified geomorphological map of the Super-Sauze landslide linking the vectors of the original positions of the most mobile reference points in August 1991 with those of October 1995. The accompanying graphs are a more accurate indication of the positions noted during successive measurement campaigns. These vectors show the main direction of the movements in the body of the unstable mass, but without regard to the time factor. The average speed value noted on the graphs are only given as an indication of the spatial distribution of the movements over the whole moving mass (the periods considered for the calculation of these values are not all the same).

There is no evidence of general movement simultaneously affecting several markers on the crown. Only two kinds of localised instabilites are noticeable: falls of morainic blocks shifted from their surrounding matrix by streaming, and landslips of limited ground surfaces (like point L on figure n° 4). This accounts for the today total disappearance of the 4-meter strip of land separating in 1991 the shepherd's hut from the main escarpment.

The three first generation points (A, B and C) on the upper shelf are no longer in use; during their follow-up periods they showed annual speeds of between 3,9 and 7,6 meter/year. The zone recording the most significant movements is immediately below the upper shelf (points 16 to 20); movements recorded here are of the order of 10 m/year and even more. This is the sector where the slopes are steepest. The vectors for points 10 to 15, placed on a transverse profile, offer a perfect demonstration of the lateral decrease in movements from the centre of the unstable mass towards its edges. Reference points 8 and 9 bear witness to the activity in the lower part of the flow, which is advancing by 1 to 2 m/year. Point 6, placed on the toe of the moving mass, gave during the two first years of measurements an average speed value of 2.2 m/year. Interesting is the behaviour of point 8 : its altitude increased with time, unlike all the other points monitored. This indicates a swelling of the lower shelf due to the pushing of accumulated material above.

Movements are also studied from a temporal point of view, in relation with rainfalls notably. The rainfall measurements used at present in these analyses are taken from the Barcelonnette station, as pluviograph readings have only been available from la Rente since 1994 and data from Super-Sauze climatological station since July 1996. The rainfall quantities are generally lower at Barcelonnette as on the landslide's site, but the variations are concomitant.

- the movements collected from six points which are typical of the whole of the Super-Sauze are given in figure n° 5. Points n° 8 and 9 are situated in the lower part of the landslide (lower shelf and toe), 13 and 14 midway and 16 and 17 upstream, just under the upper shelf. The development of the whole is the same for these six points, with an appreciable decrease in movements from upstream to downstream.

Variations in average speeds between different measurement campaigns are given in figure n°6, which also shows the number of days and the quantity of rainfall recorded at the Barcelonnette station for each period.

We observe high movement speed in two separate occasions:

- from spring 1992 to spring 1993, in relation to the heavy rainfall recorded throughout the whole of 1992, which was the wettest since 1979: the high speeds from May to September correspond to heavy rainfall in May and more particularly in June; the even higher speeds between September 1992 and May 1993 correspond essentially to heavy autumn rainfall.

- in autumn 1994, following an exceptionally showery September :

A very good correlation is evident between the heavy rains of September 1994 (234.1 mm) and the significant movements recorded for all the points between the 21st September and the 1st December. The very high speeds (some 5 times higher than the averages calculated over the whole of the four years' monitoring) recorded during this short 70-day period confirm the significant role of rainfall in some autumns. The apparent response time is around one month (high speeds in October-November after the rains of September), but it may prove to be shorter if movements accelerated at the beginning of the period from the 21st Setpember to the 1st December.

Between the two particularly wet years of 1992 and 1994, 1993 was again under the average of 730 mm established for the period from 1954 to 1994. It marks a break in the constant rise in rainfall observed since the beginning of the 1990s. The winter of 1992/1993 and more especially the first three months of 1993 were particularly dry, and there was no snow. Although a subsequent technical problem deprived us of data taken in November 1993, we note that the landslide does not seem to have moved significantly in the period from June 1993 to September 1994.

Generally, with regard to climatic conditions, we should mention here that topometric monitoring of the Super-Sauze landslide began in 1991 and coincided with the beginning in the same year of a rise in annual rainfall, which seems to be continuing to the present date. Analysis of the development of a landslide as large as the one studied here should be carried out over several decades as well as annually or pluriannually if it is to take account of all the superimposed cyclic climatic fluctuations. The displacement measurements realised during the first years permitted to quantify the global evolution of the unstable mass. The second generation survey network which became effective in summer 1996 will provide more detailled informations concerning the cinematic behaviour of the landslide in relation with rainfall and groundwater level fluctuations. This in a modelling perspective.