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Rapid mass movement as a source of climatic evidence for the Holocene

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140 figures, 20 photos, 15 tables

The frequency of landslides on the Normandy coast and their behaviour during the present climatic regime

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Summary

The coasts of Calvados (France) have 50 km of cliffs, some sectors of which are periodically affected by numerous earth movements, sometimes very extensive. The frequency of landslides in the Normandy coast and their behaviour during the present climatic regime has been approached on two time scales: the first historic and the second in the short term.

The first is based on a census of historic events, taken from various records which have been compared with meteorological conditions in order to establish the various situations which lead to the onset of here interesting phenomena. The second was a large-scale study of the Villerville and Cricqueboeuf Cirques where monitoring networks enabled us to take precise and more or less regular measurements of movements, both on the surface and in depth, of the fluctuation of the phreatic flow in relation to rainfall or freezing and thawing.

It emerges very clearly that the mechanisms are governed by rainfall. They play a decisive part in the temporal variability of movements. They have been studied on different time scales, as their role in triggering movements occurs in the rise of ground water which itself follows an annual or pluriannual cycle, spread through the season in relation to rainfall. Nevertheless we still face many difficulties in linking the two, because of the lack of data over long periods and variations in the flow were not recorded continually.

A review of all the data collected from the Pays d'Auge indicates that some areas are subjected to a quasi-permanent activity which permits the classsification of these slides as active movements.

Résumé

La côte à falaises du Calvados est soumise à de nombreux mouvements de terrain de type et d'ampleur très variable. Ils se produisent dans certains secteurs et s'échelonnent selon différents pas de temps qu'il était important de connaître. La fréquence des mouvements de terrain et leurs comportements pendant le régime climatique actuel a été abordé selon deux échelles de temps: l'une historique et l'autre à court terme.

La première a été basée sur un recensement d'événements historiques grâce à différentes archives qui ont été mises en relation avec les conditions météorologiques, afin de

rechercher les différentes situations conduisant aux déclenchements des phénomènes. La seconde a été une étude à grande échelle sur les seuls cirques de Villerville-Cricqueboeuf où des réseaux de surveillance ont permis de mesurer précisement, et plus ou moins régulièrement, les déplacements de surface et en profondeur, les battements de la nappe phréatique en relation avec la pluviométrie ou le gel-dégel.

Il ressort très nettement que les mécanismes sont commandés par les précipitations. Elles ont un rôle déterminant dans la variabilité temporelle des déplacements. Elles ont été étudiées avec des pas de temps différents car leur rôle dans le déclenchement des mouvements de terrain intervient dans l'élévation des nappes qui obéissent elles-mêmes à un cycle annuel ou pluriannuel, décalé dans la saison par rapport aux précipitations. Malgré tout, nous sommes toujours confrontés à de nombreuses difficultés pour relier les deux, en raison de l'insuffisance de données sur de longues périodes et en particulier à cause d'une absence d'enregistrement en continu des déplacements et des variations de la nappe.

1. Introduction

Along the coast of Calvados in Normandy, some parts of 50 km of cliffs are periodically affected by landslides for several centuries. Two main areas have been particulary affected, one in the west and one on the eastern side of the district (Fig. 1).

The first in a rural area between Grandcamp and St. Côme de Fresné have about 32 km of coast. The Bessin cliffs are between 10 and 75 m high, they are cut in the marly calcareous formations of Bajocian and lower to middle Bathonian. These cliffs are also affected by tectonic movements. This results in a great variability of the cliff lithologic profile, thus leading to a variety of shapes and masses which can be observed after soil movements such as rockfalls overhanging near the Pointe du Hoc and also to the east of Cap Manvieux; or small rotational landslides or plane sliding with collapse at the rear of the cliffs as observed near Le Bouffay, or sliding due to creep of the marls at the toe of the cliff as seen in the chaos of Cap Manvieux (MAQUAIRE, 1983, 1984, 1990; MAQUAIRE & GIGOT, 1988).

The second, 12 km long section between Trouville-sur-Mer and Honfleur, the Pays d'Auge plateau is bordered by very high cliffs of up to 140 m, the topographic and geologic formation of these cliffs being very varied. The profile changes from one end to the other depending on the thickness of the sedimentary support which is affected by a slight dip toward the east (MAQUAIRE, 1990). The main scarp composed of Cenomanian chalk rests on a glauconitic sand base. Below them a thick series of marly (Kimmeridgian and Oxfordian) are on top of the cornstone limestone of Hennequeville, which between Trouville and the Pointe du Heurt strengthen the cliff toe and constitute a reef flat. At the toe of the scarp the slope is more gentle and relatively straight. It is an accumulation slope of thick superficial made of blocs of chalk and debris of chalk and flint as well as loess which fill the voids between the chalk blocs. These formations have been placed in the Upper Pleistocene (FLAGEOLLET & HELLUIN, 1984, 1987).

In these two areas, two spectacular slidings occurred: one to the west (Bessin) at a location called Le Bouffay on 5 August 1981, when a whole piece of cliff (350 m long, 50 m wide) suddenly subsided (MAQUAIRE, 1983, 1990). The second was further east, in the Pays d'Auge in January 1982. At the Cirque des Graves and at Fosses du Macre near Villerville-Cricqueboeuf, a landslide totally or partially destroyed local mansions and damaged the road in several places (FLAGEOLLET & HELLUIN, 1984, 1987).

2. Studies undertaken and results available

Since 1982 a number of research projects were carried out with the objective to assess the risks associated with cliff instability in the coastal area.

2.1 Regional study: the historical inventory of earth movements

Among these was a regional study at district level based on historical records. The objective was the establishment of a spatial map of the various zones representing different potential risk levels.

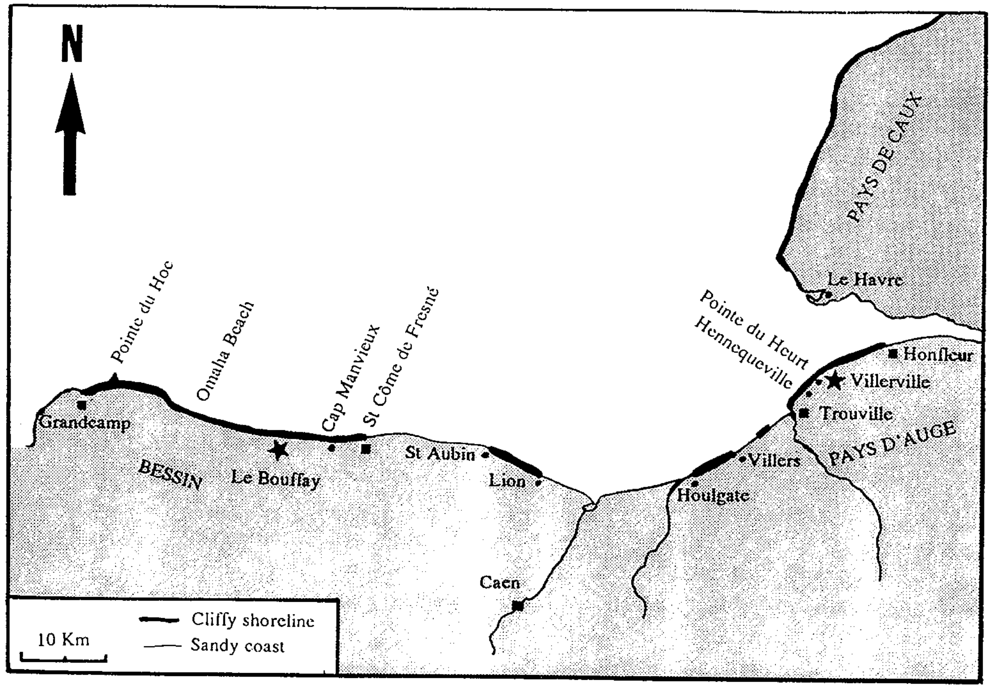

Fig. 1 Location of the main coastal cliffs on the littoral of Calvados

A historical inventory of the various types of soil movement was based on several documents, particulary the files of the district archives, and local and regional newspaper reports on landslides and other catastrophic movements (BALLAIS et al., 1984; HELLUIN, 1988). A data set of more than 300 events has been collected in the Calvados between 1879 and 1986 and their dates were known precisely.

2.2 The Villerville-Cricqueboeuf's landslide: Monitoring Networks

The second study was a detailed investigation into the Villerville-Cricqueboeuf landslide: the research objectives were to investigate the sliding kinetics of a three-dimensional model by precise topographical measurements, and also by deep displacement measurements. These measurements were made in order to find the instability factors (internal and external) and also to correlate them and to find which one was responsible for the instability and the start of the sliding phenomenon. Finally, the probability of a repeat of the event was investigated and the possible triggering level assessed. Several stability computations were performed for various hypotheses and recommendations to reduce or stop the phenomena were given.

Since 1984 a monitoring system has been installed between Villerville and Cricqueboeuf. A regular collection of the data was performed until 1988. From then until now only irregular collection was undertaken.

This monitoring system constitutes 80 bench marks cemented into the ground and their coordinates have been regularly measured with a theodolite and an EDM (electronic distance meter). Additionally three inclinometers and 21 wells and piezometers have been used to monitor the variations in phreatic water level. The development of the water table was also analysed from well records kept since 1976 (MAQUAIRE, 1990).

2.3 Methodology of studies

At each event we have associated the meteorological/climatic conditions previously and during it: the annual, seasonal, monthly or daily base (10 days intervals) rainfalls, the phases of frost and thaw. We have completed the analyses by detailed data collected over three and a half years about displacement change of piezometric levels and pluviometry.

Climatic values of St. Gatien-des-Bois station have been used and the statistical analysis of all the collected data were performed from simple or multiple correlations or from multiple factorial analysis. Effective rainfall corresponds to total rainfall, diminished by evapotranspiration (ETP), calculated by the TURC formula (TURC, 1953), which is very suitable for the climate of Normandy.

The relationship between piezometry and rainfall is established from rainfall or effective rainfall, as has been established in studies carried out elsewhere (DUTI, 1985; DELMAS et al., 1987; MATICHARD & POUGET, 1988). The synthesis of the numerous results obtained at the time of these two research studies enabled us to define the frequency of landslides on the Normandy coast and their behaviour in relation to the meteorological parameters under the present climate, in particular along the coast of Pays d'Auge.

The results of these research studies have already been published in part (MAQUAIRE, 1990). Therefore in this paper, we are only giving the strictly necessary results which are needed to illustrate the topic of this article.

3. Climatic conditions and historical landslide incidents

Qualitative analysis of the simultaneous occurrence of rain and landslides led us to choose climatic parameters close to, preceding or accompanying the landslides and some parameters more distant in time, representing the effect of delayed response after previous rainfall.

3.1 Movements observed and annual rainfall

The juxtaposition of annual rainfall diagrams and the annual number of cases recorded (Fig. 2) shows a close relationship between years of heavy rainfall and the number of movements, as, for example, in the years 1935, 1937, 1960, 1965, 1966, 1974 and 1981 to 1983. Other situations are also revealed; there are quite dry years during which cases are noted, such as 1879, 1945 and 1946, which were preceded by a period of high rainfall. At the extreme, incidents occurred during or following several dry years (with rainfall below average).

Extreme conditions combined for the particularly active period between 1978 and 1983, during which a large number of incidents were recorded. This analysis demonstrates the determining role of heavy rainfall and their succession in the onset of disturbances and stresses the importance of preceding rainy incidents.

However, some observations should not be compared with rainfall or be confused with it. Other natural factors, such as storms and periods of freezing are superimposed on rainfall in the data series and they can aggravate an already critical situation and accelerate earth movements. The various possible combinations must be examined in accordance with different time periods in order to pinpoint the periods which were effective in moving the slope.

3.2 Distribution of incidents and climatic conditions

Seventy-six per cent of incidents occurred between October and March, 19% of them in January, which shows the maximum activity (Fig. 3). Landslides were the most frequent type of movement, being 63% of the total (Fig. 3). Sixty per cent of movements occurred during a rainy period and in 75% of cases the pluviometry for the previous month was above average, 20% being over 140 mm.

Pluviometry during the three previous months was higher than the average for the three autumn months in 61% of cases and in 9% of cases it exceeded the average rainfall for the six months of autumn and winter. However, these figures must be moderated, as some 40%

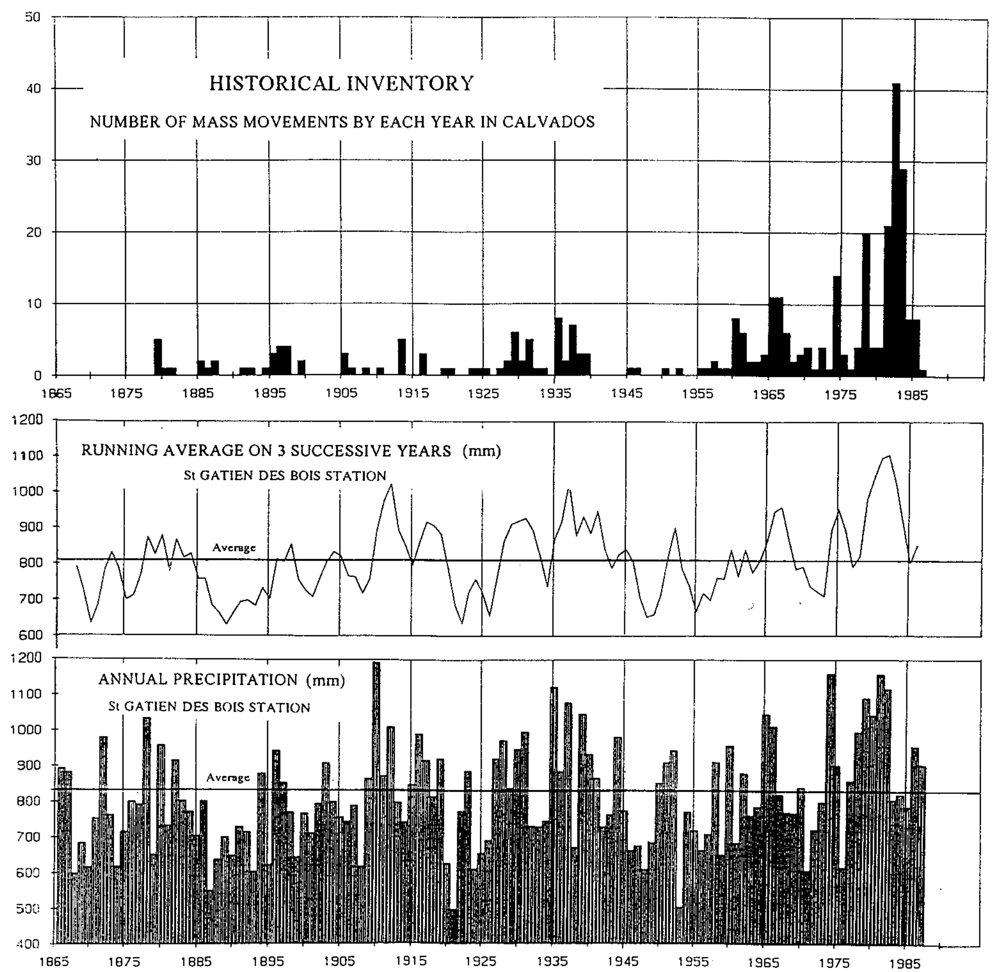

Fig. 2 Annual precipitation in relation to historical inventory between 1865 and 1986

of incidents occurred at an average quarterly rainfall which was lower than the average of 260 mm and even for levels of 90 mm. Some 90% of incidents occurred following years in which rainfall was higher than average. Twenty-five per cent of cases followed a single year and 55% occurred after three years of heavy rainfall. If we now examine the part played by storms in 139 incidents of the coastline, 57% occurred during a period of strong wind and wave activity. 40% of them immediately after or during the onset. The coincidence of low temperatures and the appearance of disturbances is low, only 29% of cases. In 10% of them, the movements occurred during a thaw and 10% during intense frost over several days.

The pluviometric characteristics and their combinations are determinant: heavy or very heavy rainfall in the preceding months or years. Landslips predominate over other types of movement and occur for the most part on the coastline of the Pays d'Auge, with a higher frequency during the autumn and winter months.

There is a general tendency to associate a distant pluriannual factor to a parameter close in time, the one succeeding the other. However, their respective influence on the onset is diffi-

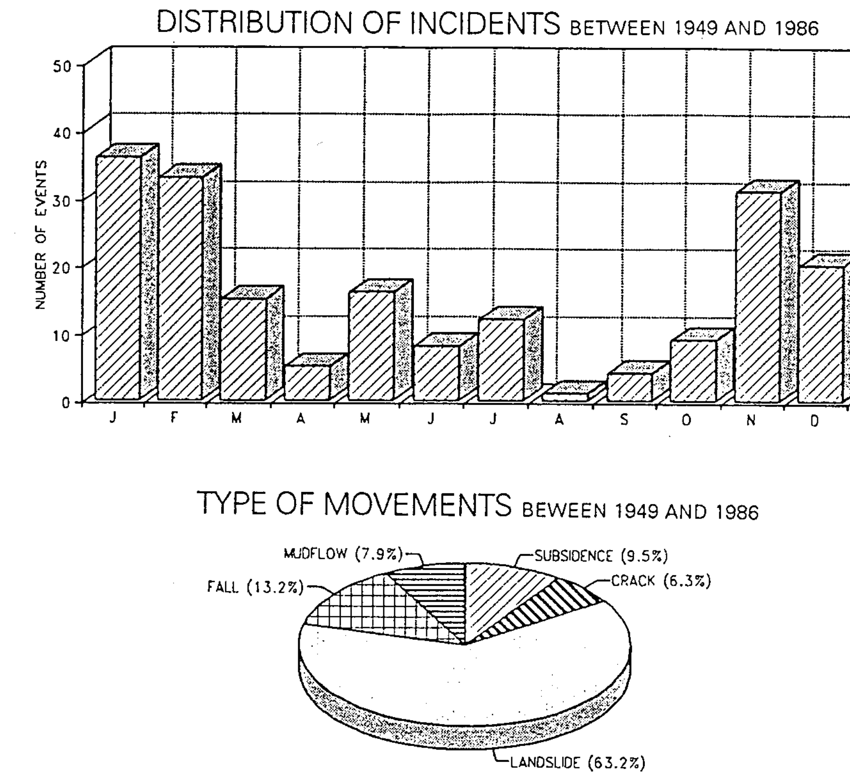

Fig. 3 Distribution and type of events between 1949 and 1986

cult to estimate. Thus the succession of several years of heavy rainfall results in the lowering of the slope's safety factor; in this case only a minimal climatic risk is needed to cause a rupture. From the forecasting standpoint, this analysis shows the advantage of monitoring climatic conditions closely over a long period, but it also demonstrates the difficulty in defining a rupture threshold which could form the basis of an alert system.

4. Movement behaviour: relationship between rain, piezometric level and movement

4.1 Seasonal variability

Movements vary with the season, and their amplitude relates closely to the climatic conditions: heavy rainfall, melting snows etc. This variation is visible on cumulative movement curves (Fig. 4). The latter are obtained from the successive movement values measured between two consecutive topographical surveys, supposing a constant speed between the measurement interval; this is inaccurate, as movements occur in sudden accelerations of unequal magnitude, followed by calm periods. The exact shape of the movements and the time at which they commenced could only have been reconstructed with a continuous measuring device (Invar wire, inverse clock). We observed similar behaviour in all the points on the slope, with considerable speeds in winter periods which corresponded to high piezometric levels. In summer periods the speeds decreased considerably in relation to the drainage of the flow.

It is difficult to determine a critical level of the flow or of an effective rainfall quantity corresponding to the commencement of dangerous and suddenly accelerating movements. The major difficulty arises from the fact that movements are not measured continuously. Attempts to establish a relationship between movements and cumulative rainfall (MENEROUD, 1983; CANUTI et al., 1985), or between cumulative movements and cumulative effective rainfall to take account of the pluviometric history, as that attempted at the Champ-la-Croix site (MATICHARD & POUGET, 1988) have not given the results expected because of the imprecision in the determination of commencement and acceleration of movements. However, we can state that sudden accelerations generally occur during the three winter months of December, up to the end of February.

4.2 Pluriannual development

At present we are happy to have a series of more or less regular measurements over eleven years between the end of 1982 and the end of 1993. These measurements enable us to see the various phases in the development of the Villerville landslip in relation to the climatic and piezometric data.

Between December 1984 and February 1988 we observe that the high water levels, and to a lesser extent the low water levels, are higher from one year to another. This pluriannual rise of the average level of flow arises from the cumulative effect of rainfall from previous years.

This development is observed in wells on the plateau for which there are long-term records available since 1976. The pluriannual rise which began in 1978 finished in April 1983. Then there was a period of several years in which the average levels decreased (Fig. 5c). This increase from 1978 coincides perfectly with the non-cyclical annual pluviometry fluctuations at the Saint-Gatien station (Fig. 2), which correspond to a period when rainfall was considerably higher than average, with a running average fluctuation calculated over five years which was 20% higher than the interannual average and which was even as much as 30% higher in 1982 (MAQUAIRE, 1990).

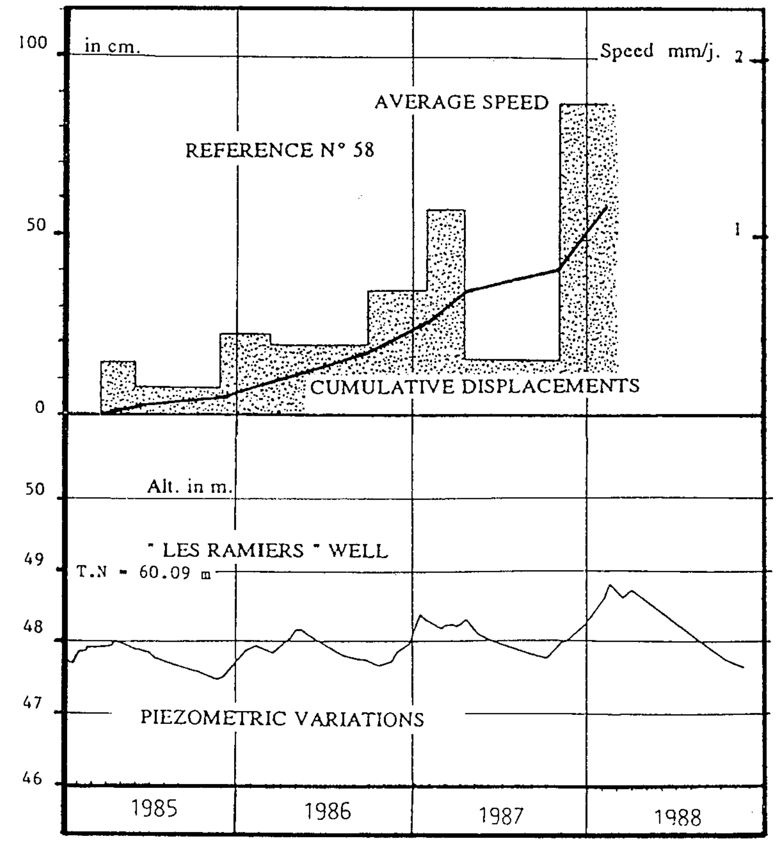

Fig. 4 Seasonal variability of movements of reference point nr. 58 and variations in piezometric levels

five years which was 20% higher than the interannual average and which was even as much as 30% higher in 1982 (MAQUAIRE, 1990).

The high level of the ground water which was observed in 1982 is in phase with the onset of the major movement of 10-11 January 1982. The extreme nature of the rain preceding this landslip is also fully demonstrated by the return periods; the annual effective rainfall (hydrological year), which are higher than ten year average. For the two or four preceding years this return period even corresponds to the maximum of the 39 years of pluviometric observation.

Thus, since the end of 1982 the subsidence measurements of the two points of the warning system along the CD 513 (Fig. 5A) and the movement of points, for example point 58 (Fig. 5B) in relation to the piezometric variations shows us the following:

- a movement deceleration phase following the major movement of January 1982.
- a movement acceleration phase since the beginning of 1985 which is demonstrated by a more or less sloping curve with the general appearance of an exponential curve on the cumulative movement curves.
- a sudden onset of movements in February 1988, leading to a sizeable landslip on the night of the 12/13 February 1988, mainly at Cricqueboeuf, which caused a good deal of damage, an extension upstream and laterally of the mobilised zone and a rise in the beach which dislodged the jetties and the breakwaters.
- then a deceleration phase for movements not wholly stable over approximately five years until the autumn of 1992 when a development commencement was recorded during 1993 in relation to the rise in the flow (Fig. 5C).

The measurements indicate that this section of the coast is subject to almost permanent activity in which landslips are amongst the active movements.

If these movement measurements fully confirm the major role of water in the onset of movements, as has already been demonstrated previously by the historic investigation, we should not forget the role of the sea, which prevents the installation of an equilibrium slope such as can be found inland in the Auge because of its erosive action at the foot of the slope. The part played by the sea has been substantiated by stability calculation models (MAQUAIRE, 1990).

5. Conclusion

The coastal cliff in Calvados is subject to numerous earth movements which vary greatly in type and extent. They occur in certain sectors and at different time rates which it is important to recognize. The frequency of landslides on the Normandy coast and their behaviour during the present climatic regime has been determined for two time scales: the first historic and the second in the short term.

The first is based on a census of historic events, taken from various records which have been compared with meteorological conditions in order to establish the various situations which lead to the onset of the phenomena mentioned. The second was a large-scale study of the Villerville and Cricqueboeuf Cirques where monitoring networks enabled us to make

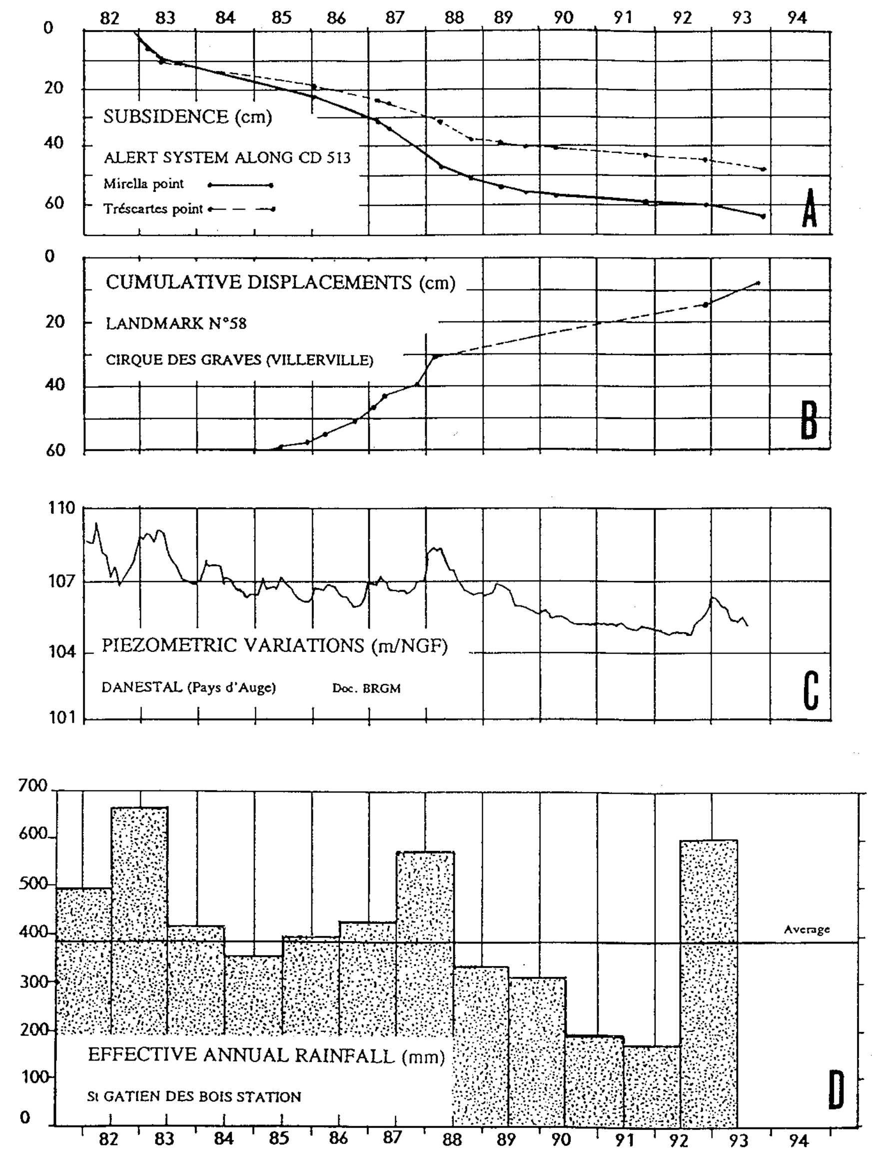

Fig. 5 Evolution of displacements of landslide of Villerville in relation to piezometric variations between 1982 and 1993

precise and more or less regular measurements of movements, both on the surface and in depth and of the fluctuation in the phreatic flow in relation to rainfall or freezing and thawing.

Statistically frost is not a factor which triggers the movement process as evidenced by the precise observations made during three severe winters. This was confirmed by a small number of events following the phases of frost and thaw, deduct from 320 cases found in the regional press.

The rainfall levels have a prevailing role in the variability of the displacements. The precipitation was studied for various time intervals because the start of movements depends on the elevation of the phreatic water table and there is a time lag between the precipitation and the movements, also the seasons have some influence on the displacements.

Therefore, attempts to establish correlations between the increase in water level and absolute rainfall have been made for different time intervals in the various analyses. It clearly appears that most of the frequent events happened during the "humid" periods. The very high water table recorded in 1982, is in phase with the beginning of the major movement observed on the 10th and 11th of January 1982. To a lesser degree, the high piezometric level recorded during the 1988 winter, corresponds to the start of the February 1988 disturbances at Cricqueboeuf.

A review of all the data collected since 1982 from the Pays d'Auge indicate that some areas are subject to a quasi permanent activity which permits the classification of these slidings as active movements.

Nevertheless we still face many difficulties in correlation the movements and the ground water level because of the lack of data over long periods and in particular because earth movements and variations in the flow were not recorded continually. Actually, a permanent system to measure movements and the phreatic level of the mass in movement wasn't yet put in place. Therefore, we continue the survey with a part of the monitoring network, with topometric measurements at a few representative points and a follow up of the flow level in one or two wells at Villerville and Cricqueboeuf. We hope to define more precisely the relationship between piezometry and movements and to install a simple warning system with an alert threshold to inform the authority in case of expected hazards.

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