Engineering Geology, 29 (1990) 241–253
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Processes of slope failure in crystallophyllian formations

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(Received September 18, 1989; accepted after revision February 6, 1990)

ABSTRACT

Giraud, A., Rochet, L. and Antoine, P., 1990. Processes of slope failure in crystallophyllian formations. Eng. Geol., 29: 241–253.

Major slope movement is a common feature of the crystalline and crystallophyllian ranges of the Alps. Beginning towards the end of the ice age, these movements have not necessarily led to slope failure but are continuing to evolve today, following a cyclic pattern, and may be a potential source of danger for human activities. A complex set of factors has to be taken into account in any study of such phenomena, particularly in attempting to predict when the final crisis will occur.

A particular feature of crystallophyllian massifs is their pre-existing anisotropic structure (schistosity, metamorphic foliation), in which weakness planes give rise to mechanical anisotropy.

To analyse the failure processes that may occur in such a context and affect an entire mountain slope, the authors consider several examples, most of which are located in the French Alps. The study is based mainly on surface observations.

FAILURE MECHANISMS INFLUENCED BY FOLIATION

Dip in foliation follows slope

A landslide occurred at Charmonétier, near Bourg-d'Oisans in the Isère department of France, on 24 August 1987. Some 200 000 m^3 of material were involved, reaching a maximum depth of 10 m (Fig.1).

The landslide occurred in migmatitic amphibolites with a natural slope of 35°–45° and foliation inclined at 25°–45° towards the valley. The foliation forms potential slip planes with a dip of the same order of magnitude as the angle of friction that might be expected in this type of material covering such areas.

There is thus a latent potential for landslides to occur in this type of structural context, and only slight modifications in the physical or hydraulic characteristics of the rock mass are needed to trigger them off.

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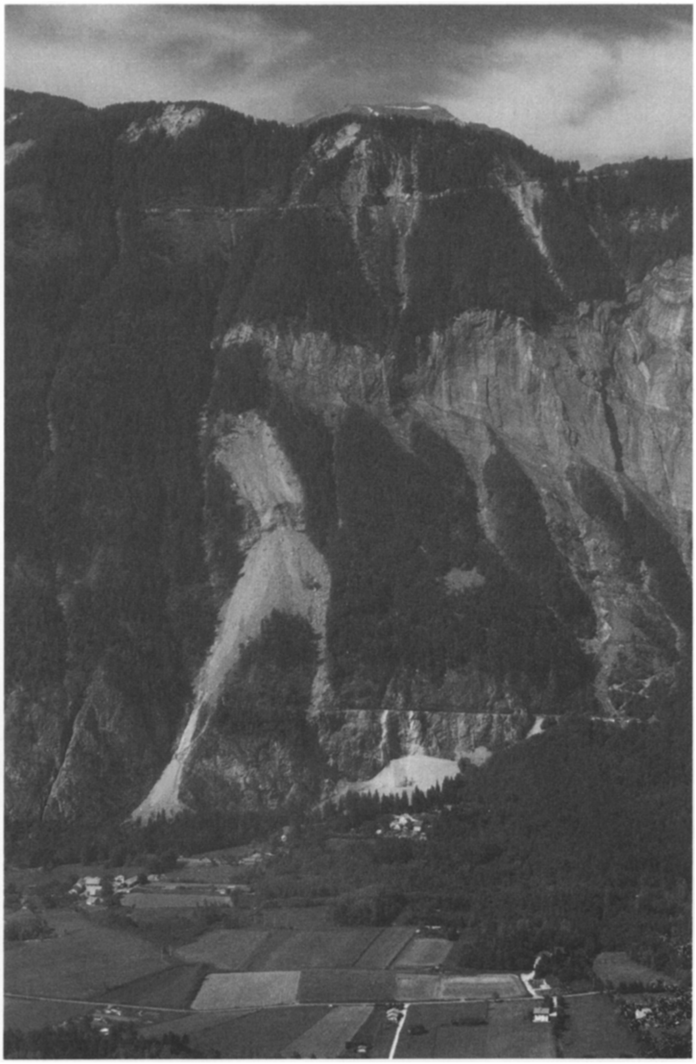

Fig. 1. View of the Charmonétier landslide.

Foliation strike is parallel to slope and dip almost vertical

(a) *Billan landslide (Isère)*

The landslide at Billan (Dubie and Guitton, 1988), on the right bank of Grand-Maison reservoir, lies on a relatively homogeneous slope (average angle of 35°) over a vertical distance of the order of 400 m.

The slide, which revived in spectacular manner in the spring of 1986, is of a

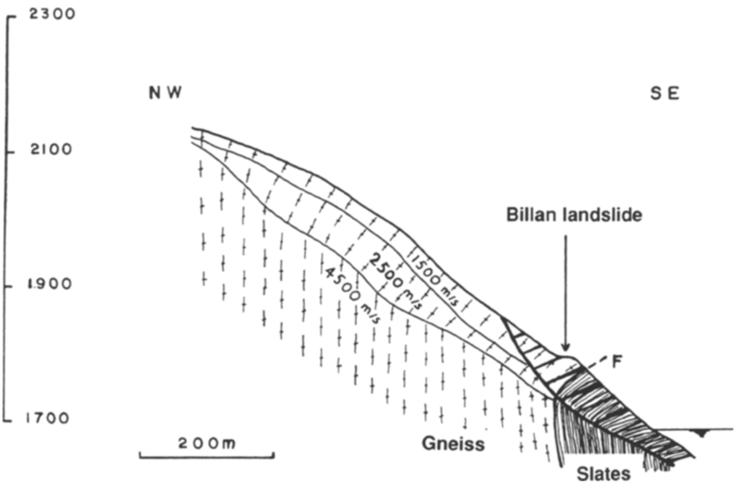

Fig.2. General slope profile of the Billan landslide (after Dubie and Guitton, 1988).

composite type. A recent slide overlies an old toppling failure in the crystalline gneisses and Lias schists.

Seismic investigations performed at the site do not reveal any distinct unconformity between the slide formations and underlying substratum. In contrast, the progressive increase in seismic velocities with depth (badly fractured gneiss = 1500 m/s, fractured gneiss = 2500 m/s, sound gneiss = 4500 m/s) clearly demonstrates the effects of the toppling phenomenon occurring over a depth of about one hundred metres.

The area concerned by the slide is of the order of 5 ha, while observations indicated a maximum depth of 65 m (Fig.2).

(b) *La Clapière landslide (Alpes-Maritimes)*

A similar structural context is found at the Clapière site (Blanc et al., 1987; Follacci, 1987) in a rock mass consisting of migmatitic gneiss with almost vertical foliation that has undergone widespread toppling over a distance of several hundred metres (Fig.3).

The slide covers an area of about one hundred hectares and rises a vertical distance of 600 m. It arose in the toppled formations and has undergone severe deformation since 1977 (Fig.4).

FAILURE MECHANISM INFLUENCED BY FRACTURING

Major fractures dip in conformity with slope

Depending on the scale of the discontinuities in the rock mass, either of the following may occur: (1) localised failure (unstable blocks), involving small volumes of material that can be handled by the conventional removal or consolidation

Fig.3. General view of La Clapière landslide.

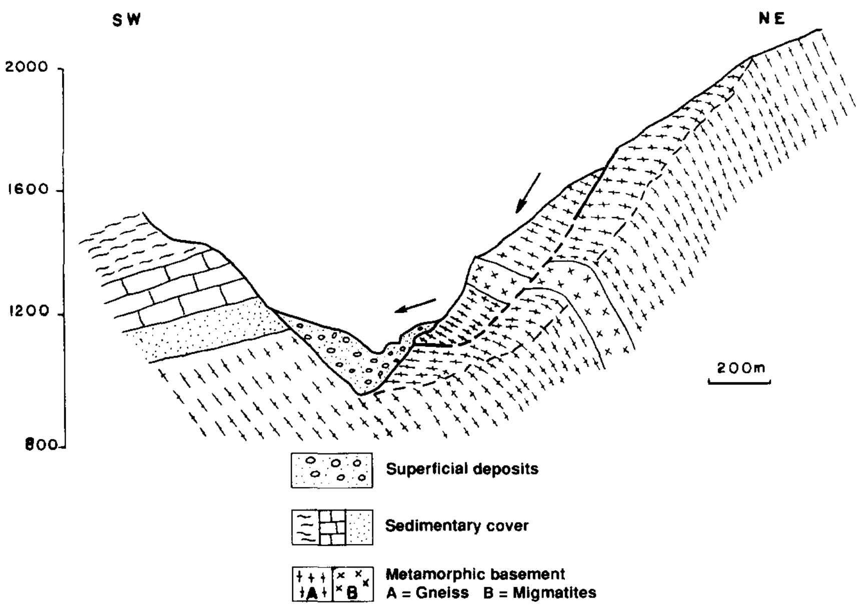

Fig.4. Geological cross-section of La Clapière landslide (after Follacci, 1987).

methods; (2) large-scale failure, giving rise to large landslides affecting entire mountain slopes. This type of phenomenon has occurred and is still occurring in very many parts of the crystalline and crystallophyllian ranges of the Alps, and the Romanche valley near Grenoble provides numerous examples.

Major fractures parallel to the slope and almost vertical

There is a serious threat of landslides occurring along the right bank of the Romanche in the so-called "Ruines" area near the village of Séchilienne (Isère). Here, the mountainside consists of micaschists with subvertical metamorphic foliation at right angles to the valley. This family of discontinuities therefore has no direct effect on the stability of the rock mass.

Geological and geomechanical studies carried out at the site (Antoine et al., 1987) revealed evidence of considerable instability up to the summit of Mont Sec (1100 m). The area affected is of the order of one hundred hectares, and movement probably began with the last glacial retreat.

The middle section of the slope, where movement appears to have been greatest (involving an estimated 2–3 million cubic metres of rock), lies in the general area of instability running up to the summit of Mont Sec. It is therefore reasonable to assume that there is a risk of a massive landslide occurring, which could involve as much as 10–20 million cubic metres (Fig.5).

The major fractures at the site run ENE–WSW, and are clearly distinguished by characteristic depressions in the rock morphology sometimes more than 20 m wide, attesting to the great age of gravity-induced movement (Fig.6).

Movement and deformation have occurred in a roughly NNE–SSW direction in the upper part of the slope (above 1000 m) and in a NNW-SSE direction lower down, i.e. virtually at right angles to the general strike of the major fractures (Fig.7).

This modification in the displacement trajectory demonstrates the complexity of the phenomenon, the main underlying factors being the geological, glacial and hydraulic boundary conditions.

MOVEMENT CHARACTERISTICS

Movements with pre-existing failure surfaces

For this type of landslide to occur, a sufficiently large failure plane must already exist. Furthermore, this plane must intersect with an unconfined surface for movement to take place. Thus, the greater the thickness of rock considered, the lower the probability of occurrence.

For this reason, movements connected with plane slip mechanisms generally affect shallower areas than those in which there is no pre-existing slip plane.

Consequently, the volumes of rock involved are ususally smaller when the failure planes consist of closely spaced discontinuities (foliation planes), as in such cases the thickness of the unstable area is determined by surface weathering mechanisms.

Fig.5. General view of the right bank of the Romanche valley at the Ruines de Séchilienne site.

Thus, in the case of the *Charmonétier landslide* mentioned above (p.241), the slip area was no more than 10 m thick.

Major slope movements with no pre-existing slip surface

In these cases, the failure mechanism penetrates more deeply into the rock mass, causing dislocation (i.e. a succession of microcracks) that may descend several hundred metres.

Instability in these cases is a result of cracks spreading to an entire area and causing it to move.

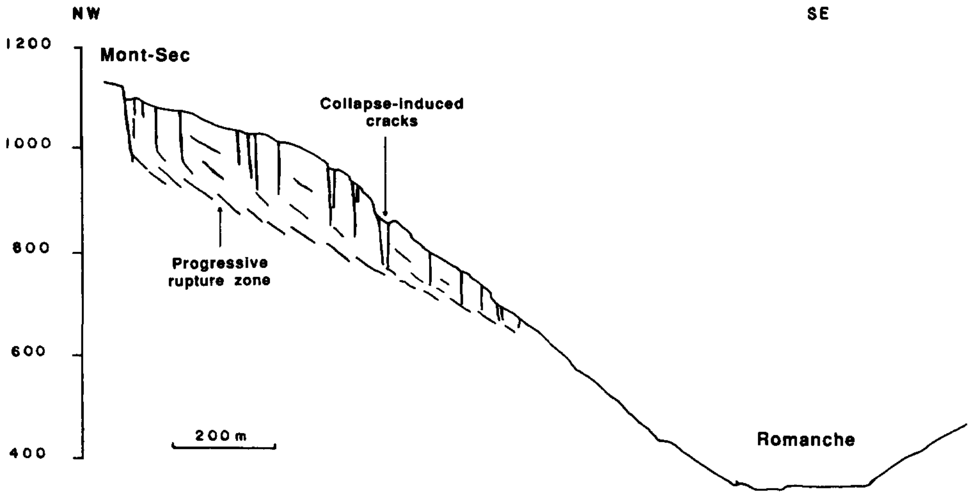

Fig.6. Sketch cross-section of the Ruines de Séchilienne site.

DEVELOPMENT OF FAILURE MECHANISM

A landslide is generally the final stage of failure, after the entire rock mass has been gradually weakened.

Movements with pre-existing slip surface

This type of failure corresponds to slip mechanisms of the translational or rotational type associated with weaker structural surfaces where shear and slip phenomena are most likely to occur. As the failure mechanism develops along the base surface, shear strength is progressively diminished for one of two main reasons: (1) deformation develops, resulting in a regression from peak strength to residual strength; (2) weathering phenomena develop, resulting in a progressive attenuation of strength characteristics. Generalisation of the above mechanisms results in failure.

The present conditions of stability of a rock slope depend partly on the degree to which it has progressed towards failure, i.e. on the degree of regression already reached by the rock mass. This may be especially advanced along surfaces where displacement has already occurred (such as fault planes or old slip surfaces, for example).

This is how the *catastrophic Valtellina rockfall* occurred in Italy on 28 July 1987, involving an estimated 30 million cubic metres of crystalline and crystallophyllian material. The slide developed along pre-existing fracture planes forming a huge dihedron which, in addition, had already undergone major displacement, probably in the post-ice age period.

Movements with no pre-existing failure plane

In these cases, the failure mechanism exploits unconformity networks, which are naturally weak. As there is no pre-existing basal failure plane, a process of strength

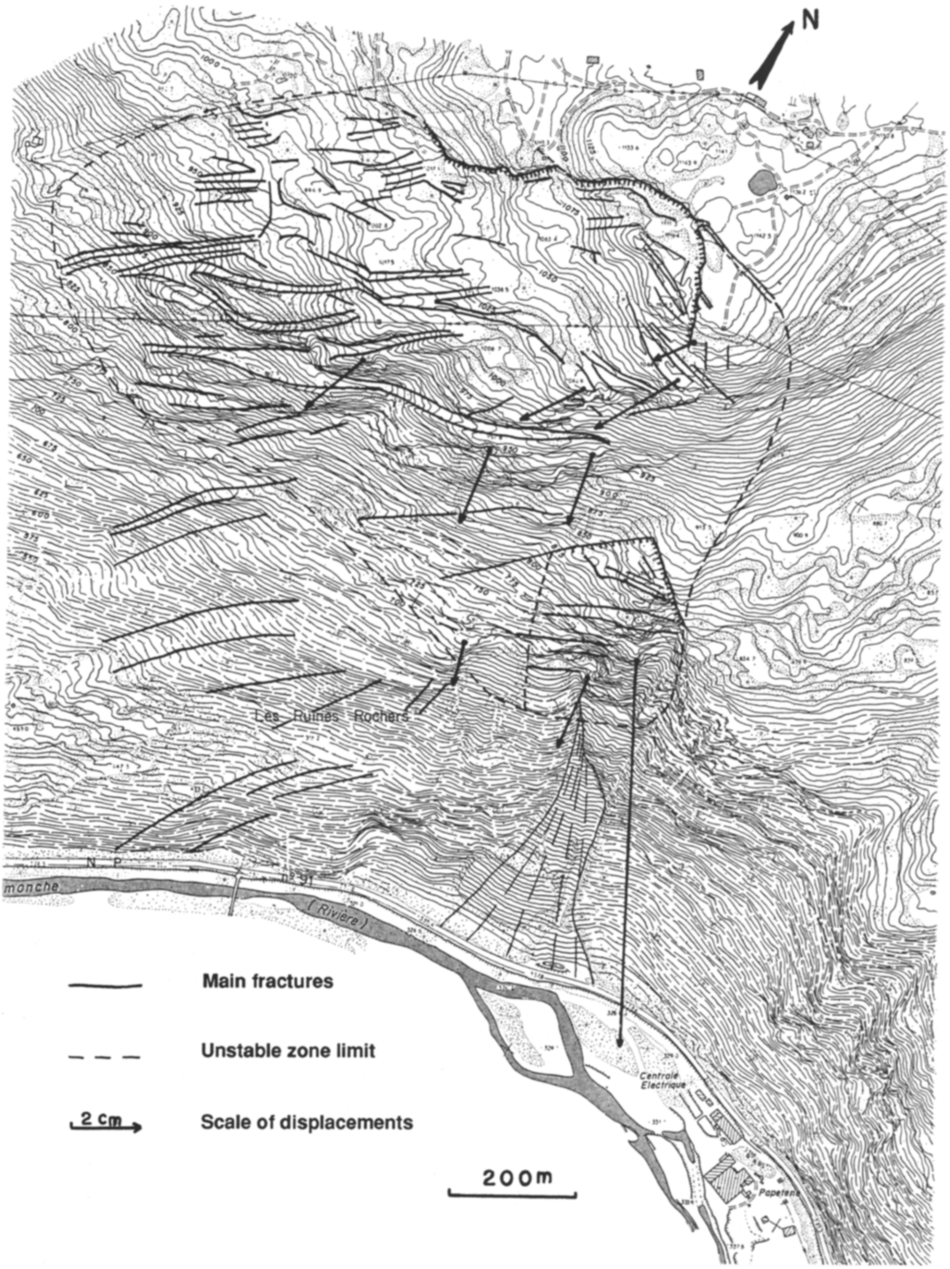

Fig.7. Direction of displacement vectors between February and November 1988 at the Ruines de Séchilienne site.

characteristic regression occurs over a limited and ill-defined area, located more deeply within the rock.

Failure mechanisms may occur in several forms:

(a) *Toppling*

This very frequent mechanism is characterised by normally upright structures tilting near the surface as a result of gravity. In crystalline and crystallophyllian rock masses, toppling can only occur if there is a pronounced pre-existing anisotropic structure (schistosity or foliation) dipping into the rock, with a strike running more or less parallel to the general direction of the slope (Goodman and Bray, 1976).

Toppling is generally accompanied by shear failure at the interface between successive beds of rock. The discontinuities enabling toppling to occur may also correspond to a prevailing direction of fracturing (Caine, 1982; Holmes and Jarvis, 1985).

A recent example of this type of movement is the major landslide that occurred in May 1989 in the *Sept Laux range on the right bank of the Eau d'Olle valley*, not far from the Grand-Maison dam. The rockslide, involving more than 400 000 m^3 of material, occurred in a granite massif when a section of cliff broke away. This cliff supported part of the mountainside in which toppling had been caused by a prevailing family of roughly vertical discontinuities running parallel to the valley (more or less E–W).

In the long term, toppling generally gives rise to the formation of a fracturing system developing and spreading progressively at the base of the toppled blocks, resulting in a basal failure strip. This strip may facilitate surface movement caused by a completely different process (approximately planar slipping).

(b) *Sagging*

Sagging occurs as a result of internal failure within the rock mass, causing it to collapse on itself. Cracks develop and spread to the entire unstable rock mass, without there being any clearly identifiable failure surface (Voight, 1979; Hutchinson, 1988).

Certain structural conditions favour the development of this type of phenomenon: (1) pre-existing anisotropic structure, such as schistosity or foliation, giving rise to anisotropic mechanical strength; (2) weakness planes intersecting obliquely with other fracture systems; (3) adverse direction of the stress field.

For this reason, given their structure and tectonic history, crystallophyllian rocks are especially prone to this type of event. Failure may be triggered off by various factors: (1) severe stress concentrated in abutment areas and a reduction in rock strength as a result of weathering; (2) decrease in confining stresses (failure as a result of decompression or elimination of an abutment); (3) hydraulic failure; (4) dynamic overloads (earth tremors).

In the case of glaciated valley slopes, the major variations in stress associated with the advance and retreat of the glaciers and the resultant pore pressure have severely attacked the rock masses and are a prime cause of failure.

The development of sagging is closely linked with the boundary conditions of the rock mass, and in particular with the setting up of confining stresses associated with dilatency of the rock. As failure and deformation spread through the basal area, a failure strip and clearly defined failure surface may be formed, leading eventually to a slip and possibly severe rockfall.

Though extremely complex, *the Séchilienne site* mentioned earlier (p.245) is a good illustration of this type of evolution, where failure gives rise to gravity-induced sagging and expansion corresponding closely with the structural data and analysis of observed displacements.

(c) *Rotational slipping*

This type of mechanism, which is common in soils, also occurs in rock masses and generally represents the final stage of development of one of the mechanisms discussed above. In a vertical section, failure development is generally concentrated in a shear zone. Following extension of this shear zone a basal slip surface may be identified.

As in the other cases mentioned above, the failure mechanism will take advantage of areas of weakness in the rock, i.e. discontinuities, which may be structural (schistosity, foliation), lithological or tectonic (fracture systems within the rock). These favour the development of failure mechanisms on a relay basis, associated with multiple local matrix-type failure at stress concentration points.

In its present state, *the Clapière landslide* provides an example of a rotational slip superimposed on general toppling of the slope. Several distinct movements may be identified as the phenomenon progresses, along with a modification of water flows within the rock mass, due to considerable changes in permeability over time and probably in space as a result of deformation of the massif.

(d) *Summary*

Up to a certain stage of development, toppling and sagging mechanisms may give rise to progressive deformation of the rock mass without causing any sudden loss of stability. This may occur as a result of modifications in boundary conditions (elimination of toe abutment or lateral confinement or stresses exerted by the glacier) or following progressive loss of internal strength in the rock.

CONDITIONS PRIOR TO FAILURE

In the final stages of development, as stability is gradually lost, a limit state is reached beyond which the dynamic phase of failure occurs, giving rise to a rockfall or landslide.

Contributing factors

With each of the various failure mechanisms discussed above, hydraulic factors play a vital and generally decisive role.

Hydraulic pressures are of a comparable order of magnitude to gravity stresses, setting up tractive forces in the rock in the direction of least resistance (hydraulic failure of discontinuities). In addition, by reducing effective stresses, they cause a significant loss of shear strength (reduction of friction component).

This all points to the considerable importance of hydraulic factors in the later stages of failure development. A further contributing factor is the fluctuation in hydraulic conditions as a result of seasonal changes in the weather. Stresses and deformations in the rock mass vary according to the different cycles of hydraulic loading, causing the failure mechanisms to progress in an irreversible manner.

Thus, in the Alps, most of the major landslides occurring at present are caused by the reactivation of movements that started with the retreat of the ice some 10 000–15 000 years ago. As the glaciers supporting the rock masses retreated, torrents and rivers often deepened the valleys, with the result that pre-existing slips that had not yet reached failure point have been reactivated.

Current monitoring of several major slides shows that they go through phases of stabilisation and reactivation, which may last several years or decades, if not more. These phases of activity and calm are closely dependent on geological history (namely the extent of weathering and neotectonic movements) and climatic factors. Indeed, climate, like hydraulic factors, must be considered a major contributor to weathering processes, hence to a decline in rock strength and the spread of dislocation mechanisms.

Neotectonic movements and earth tremors during recent and present time also help to cause deformation and set up stresses in active areas, thus contributing to a decline in the stability of the upper parts of the rock masses.

Triggering factors

The extra amount of energy needed to trigger off the dynamic phase of movement, leading to failure proper, is small in comparison with that involved during the preceding loss of stability.

Several factors may set off a slide: (1) hydraulic factors, given the decisive role of pore pressure in actual failure; (2) earth tremors, exerting a dynamic overload on the rock mass; and (3) a decline in the strength of the rock mass, so that it falls below a critical stability threshold. The result will be the same, though far less sudden.

Failure

(a) *Movements with pre-existing failure surfaces*

In these cases, there is a sudden reaction to an exceptional influence, which may be due to the climate (heavy rains, severe snowmelt) or another factor (an earth tremor, for example) and the dynamic phase of instability is reached very quickly.

It may be noted, in addition, that the mechanism behind these movements is hardly modified by changes in the phenomenon itself. Thus, *the Valtellina landslide* (Italy) 28 July 1987 occurred after torrential rain, with as much as 60 mm/h, had fallen between 15 and 22 July.

(b) *Movements without pre-existing failure surfaces*

These generally progress more gradually to the point of failure. There is usually a cyclic annual component, connected with fluctuations in climatic factors that affect hydraulic conditions in the massif.

In parallel with the development of failure, which is both progressive and discontinuous, as seen above, the failure mechanism itself is modified by the phenomenon: different failure mechanisms occur; several mechanisms are superimposed; certain slip areas are distinct; slow deformation of the slope has an effect on the phenomenon itself.

These movements may stabilise themselves or, in contrast, accelerate the phenomenon in certain places.

In the *case of Séchilienne*, analysis of the monitoring results obtained since 1985 clearly shows a cyclic variation in displacement velocities, connected with the hydraulic regime of the massif. Measurements show a major increase in velocity (in the ratio of 1 to 5) during the winter and spring. The slower acceleration observed during the winter of 1988–89 may be linked with the lack of rain and snow during this period.

Observations of displacement velocities at *the Clapière site* between 1982 and 1987 reveal a characteristic response of the massif, consisting of an increase in velocities (in the ratio of 1 to 4) between May and July, corresponding with the snowmelt period. Since 1987, development of the failure has been accompanied by a change in the behaviour of the rock mass, with average velocities decreasing and an attenuation in the snowmelt response.

With movements such as these, where there is no pre-existing failure surface, failure may be set off when a particular threshold is temporarily exceeded during a particular season, sometimes as a result of an exceptional event. It is therefore difficult to evaluate the final critical stage of development, as a major natural seasonal component is involved. Moreover, modifications in the behaviour of the rock mass caused by the development of the failure mechanism itself or by inherent deformation prevent the establishment of a reliable forecasting model based on extrapolation from past behaviour patterns.

CONCLUSION

The various types of failure which may occur in a crystallophyllian massif are governed by the geometric characteristics of its discontinuities. As shown above, the behaviour of a rock mass bisected by a continuous fracture is quite different from that in which the various constituent elements are interlocked (i.e. in which there is no prevailing family of fractures).

As far as failure mechanisms are concerned, they must be seen as the product of a set of processes affecting the rock mass over time and causing a decline in its natural level of stability, with actual failure representing the final stage.

On the basis of these factors, the method of study to be followed includes: (a) structural studies, leading to definition of the geometric aspects of the instability; (b) preparation of a model of possible failure, using the structural data and results obtained from monitoring; and (c) approximate representation of the mechanism involved and definition of a likely lead-up to actual failure.

REFERENCES

Antoine, P., Camporota, P., Giraud, A. and Rochet, L., 1987. La menace d'écroulement aux Ruines de Séchilienne (Isère). Bull. Liaison Lab. P. et Ch., 150/151: 55–64.

Blanc, A., Durville, J.L., Follacci, J.P., Gaudin, B. and Pincent, B., 1987. Méthodes de surveillance d'un glissement de terrain de très grande ampleur: La Clapière, Alpes-Maritimes, France. Bull. Int. Assoc. Eng. Geol., 35: 37–46.

Caine, N., 1982. Toppling failures from Alpine cliffs on Ben Lomond, Tasmania. Earth Surface Processes and Landforms, 2: 133–152.

Dubie, J.Y. and Guitton, C., 1988. Radio-transmission of monitoring of a landslide inaccessible during winter: Grand-maison reservoir, Billan landslide. Proc. Fifth Int. Symp. Landslides, Lausanne.

Follacci, J.P., 1987. Les mouvements du versant de la Clapière à Saint-Etienne-de-Tinée (Alpes-maritimes). Bull. Liason Lab. P. et Ch., 150/151: 39–54.

Goodman, R.E. and Bray, J.W., 1976. Toppling of rock slopes. Proc. Specialty Conf. Rock Engineering for Foundations and Slopes. ASCE, Vol. 2, Boulder, Colo.

Holmes, G. and Jarvis, J.J., 1985. Large-scale toppling within a sackung type deformation at Ben Attow, Scotland. Q. J. Eng. Geol., 18: 287–289.

Hutchinson, J.N., 1988. Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. Proc. Fifth Int. Symp. Landslides, Lausanne.

Voight, B., 1979. Rockslides and Avalanches. Elsevier, Amsterdam.