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The Séchilienne landslide

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9.1 INTRODUCTION

The Séchilienne landslide has developed on the right side of the Romanche valley, 20 km to the south-east of Grenoble in the Isère Departement of the French Alps (Fig. 9.1). The national road RN 91 runs along the valley bottom and then to the Lautaret Pass (the link from Grenoble to Briançon and Italy), one of the higher alpine passes which is not closed in winter. Except for a narrow winding road, the RN 91 is the only access to numerous ski resorts as L'Alpe-d'Huez and Les Deux-Alpes.

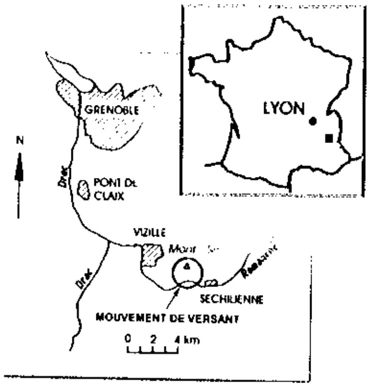

Figure 9.1. Location map of Séchilienne.

9.1.1 *Landslide description*

The landslide is occurring on a slope extending from an elevation of 330 m a.s.l. at the bottom of the valley to 1150 m a.s.l. at Mont Sec (Fig. 9.2). The landslide itself extends from 600 m a.s.l. up to 1130 m a.s.l., over an area of approx. 70 ha. The limits are as follows:

- to the east: a major tectonic shear zone (N 20°), which is a clear-cut border,
- to the north (upwards): a scarp which has probably been formed by a large post-glacial sagging,
- to the south (downwards): the slope below 600 m a.s.l. is not moving,
- to the west-south-west: the movement is assumed to decrease continuously.

The landslide can be divided into three principal areas (Fig. 9.3): the frontal mass, the most active (several decimetres per year; source of many rockfalls) and disrupted part, the volume of which can be estimated at approximately 3 hm^3; an intermediate zone with medium activity; the upper and north-western part, corresponding to an elliptic (probably) post-glacial sagging, with low velocities.

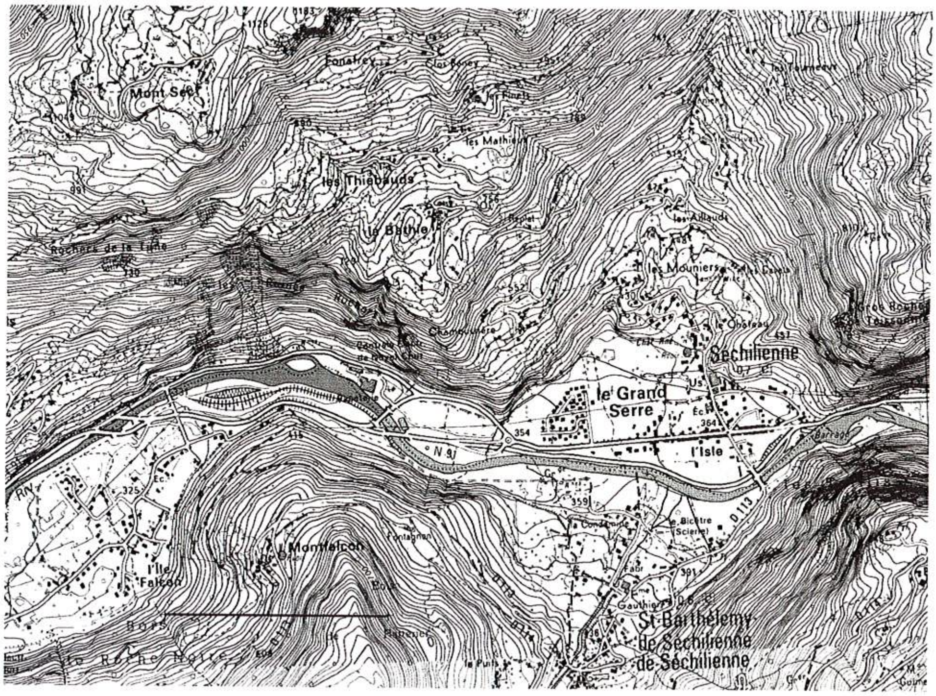

Figure 9.2. General map of the site of Les Ruines de Séchilienne (IGN map).

Figure 9.3. Aerial view of the frontal mass. The Séchilienne plain can be seen in the background.

9.1.2 *Historical background*

Many rockfalls have been reported during the last centuries resulting from the right side of the Romanche valley at the site currently called "Les Ruines". Some mining activity (metallic sulphurs) was carried out in the XIXth century and ended after the 1st World War. The oldest aerial photographs (1937 and 1948) show a slope morphology with elliptic sagging and NE-SW trenches and active screes. But it may be seen that a footpath remained passable through the frontal mass until after World War II.

An important reactivation was observed in the 1980's: rockfalls hit the national road RN 91 during the winter of 1985 and the existence of a large slope deformation was recognized (Antoine et al., 1987). Monitoring of the slope was set up and some protective measures were installed: a fence with an electrical wire alarm and traffic lights along the original portions of the RN 91, a dam with a storage volume capacity of about 2 hm^3 of debris and a diversion river bed for the Romanche River.

In 1986, a diversion road was opened to traffic; it lies in the middle of the valley on the other side of the river (the initial road ran along the foot of the slope) and it is, therefore, safe from rockfalls but remains exposed to rockslides of more than 1 or 2 hm^3 (Fig. 9.4). In 2003, a diversion gallery was driven in the opposite slope for the Romanche River.

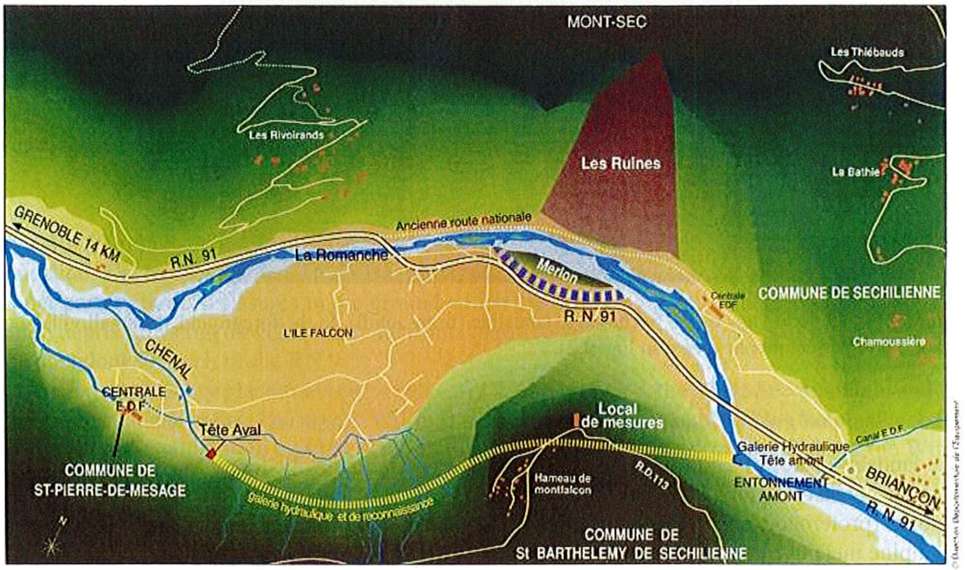

Figure 9.4. Sketch of the main features of the site of Les Ruines: see particularly the original trace of the RN 91 (ancienne route nationale) and the dam (Merlon).

9.2 REGIONAL FRAMEWORK

9.2.1 *Climatic and water conditions*

The annual rainfall in Grenoble is nearly 1 m per year. Average rainfall (and snowfall) on Mont Sec can be estimated at about 1200 mm per year. High intensities occur mainly during the autumn rainfall, but water infiltration may be important during snow melting periods. No springs are present on the landslide slope.

9.2.2 *Regional morphology*

The higher peaks in the vicinity of Les Ruines are the Pic de l'Oeuilly (1500 m a.s.l.), north of the valley, and the Grand Serre (2140 m a.s.l.) to the south.

The Romanche valley has an average east-west orientation. It is a typical glacial valley originating near the Lautaret Pass. In front of Les Ruines, the valley is rather narrow (220 m) but enlarges upstream (Séchilienne village) and downstream (L'Ile-Falcon, small village) (Fig. 9.5).

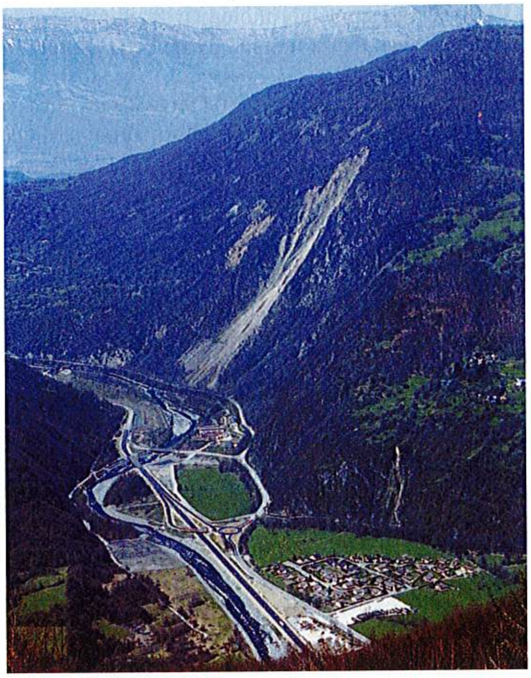

Figure 9.5. General view of the Séchilienne landslide (from uphill). In the foreground, the small village of Grand Serre in Séchilienne (see also Fig. 9.2).

9.2.3 *Regional geology and structural setting*

The landslide takes place in the external part of the crystalline Belledonne Massif in the French Alps. It consists mainly of micaschists resulting from the metamorphism of old sedimentary deposits (proterozoic or early paleozoic age). The main metamorphic episode is the hercynian one; the alpine metamorphism is less pronounced (INTERREG 1996; Pothérat & Alfonsi, 2001).

Several tectonic episodes folded and faulted the massif during the hercynian and alpine tectonic phases. The quaternary uplift of this part of the alpine chain is not yet complete.

The geological unit ("série satinée"), which includes the Séchilienne landslide, is bordered on the western side by the Vizille fault and on the eastern side by the "median" syncline; both structures have a N 20° azimuth, which is the elongation direction of the Belledonne Massif (Fig. 9.6).

9.3 HAZARD ANALYSIS

9.3.1 *Geomorphological analysis*

The Romanche River flows from east to west in the alluvial plain. Geophysical investigations performed in the valley in front of Les Ruines showed that the bedrock lies nearly 100 m below the alluvial plain.

The south-facing slope of Les Ruines has an angle of 45° in its lower part and about 20° in its upper part and near the crest. The main feature of the slope is the sagging of Mont Sec, bounded

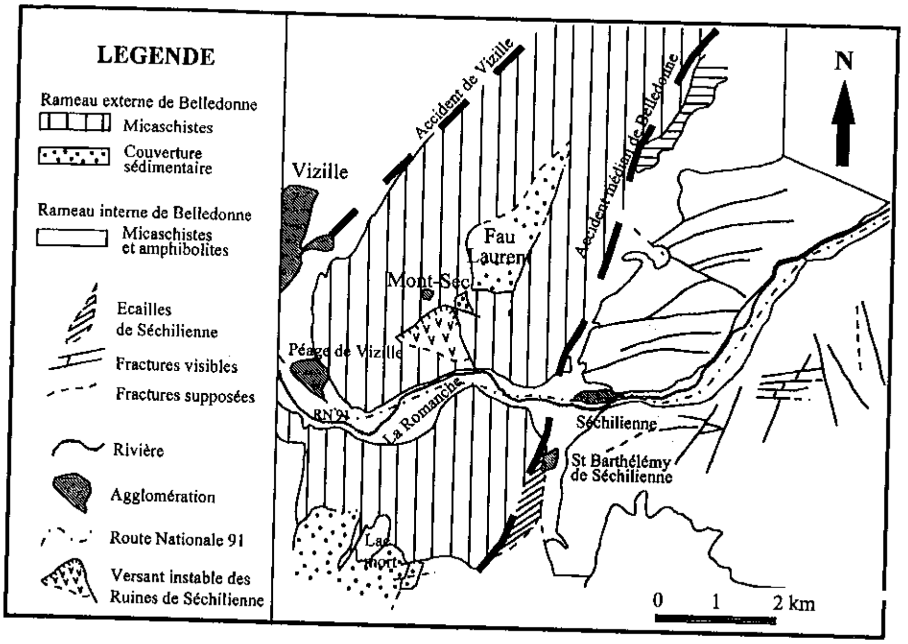

Figure 9.6. Geological sketch of the Séchilienne area.

by a 40–50 m high scarp with an elliptic shape. Several trenches N 70° cross the upper part of the landslide. The frontal zone (south-eastern part of the landslide) is presently wholly disrupted in its upper part, with deep fissures in the ground which are broadening and collapsing. Rockfalls and small debris flows run downhill from the frontal part (corridor of Les Ruines) and frequently reach the abandoned stretch of the RN 91.

Ancient quaternary glaciations (Riss and early Würm) covered, the Mont-Sec mountain and the present Romanche valley. During the Würm II period (−90 000 to −40 000 BP) the glacier covered the Mont-Sec mountain and filled the Romanche valley up to 1200 m a.s.l. During the Würm III period (−35 000 to −25 000 BP) the glacier was not higher than 600 m a.s.l., which is the level of the bottom of the moving zone.

9.3.2 *Local geology and structural analysis*

The metamorphic rocks (greenschist facies) that make up the slope are rather heterogeneous: micaschists (ancient pelitic rocks and sandstones) with variable quartz content producing variable resistance to weathering and erosion. To the north-east of Mont Sec, the metamorphic rocks are locally covered by carboniferous conglomerates or Mesozoic sediments.

Two main structural alpine directions are present at the site:

- strike-slip faults striking N 20–30° to the right, parallel to the "median" syncline,
- strike-slip faults striking N 120–140° to the left, conjugated to the preceding ones.

These faults divide the moving zone into four parts (Fig. 9.7). The geodetic measurements carried out over the past 20 years are fully coherent with these structural features.

The elliptic sagging of Mont Sec may be related to a cone-sheet structure due to a deep magmatic intrusion, possibly of Permian age (Fig. 9.8). This may be correlated to the radial and concentric filonian structures with sulphur mineralisation.

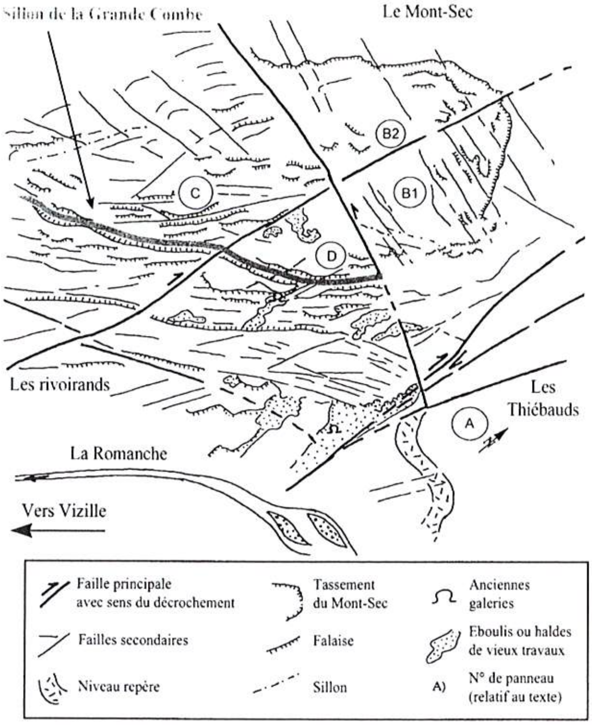

Figure 9.7. Structural sketch of the Séchilienne landslide. Zone A is stable. Zones B1, B2, C and D are formed by two conjugated faults. Thick lines: main faults. Thin lines: secondary faults.

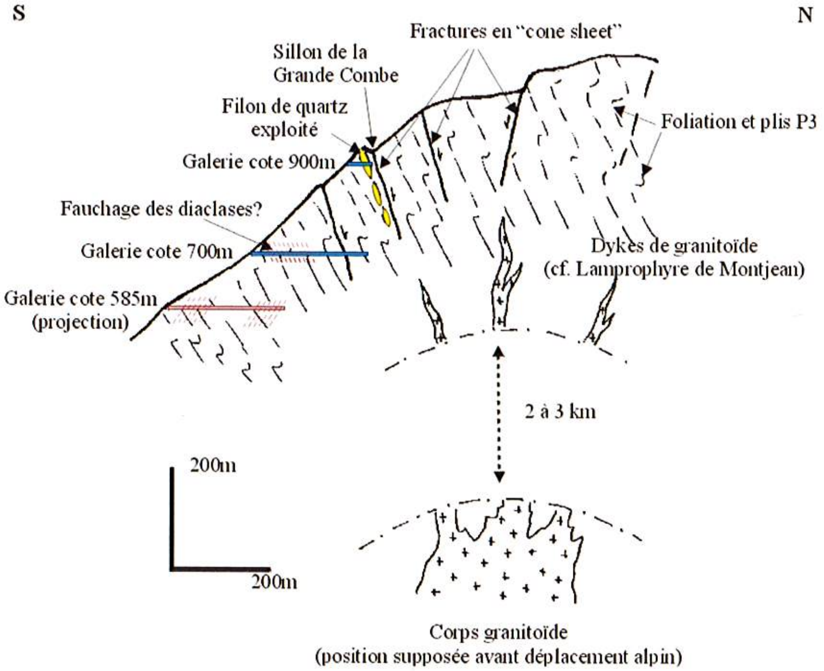

Figure 9.8. Geological section through the "sagging" of Mont Sec.

9.3.3 *Investigation and monitoring*

The geological survey included aerial photo interpretation, field observations, geological mapping, geophysical exploration and the boring of a 240 m long horizontal gallery (710 m a.s.l.). The cost of the gallery was about 380 k€.

Basic monitoring of the slope was set up by the Centre d'Etudes techniques de l'Équipement de Lyon (CETE) in 1984 (Evrard et al., 1990; Duranthon et al., 2003) and it was then progressively increased: wire extensometers, geodetic measurements of points on the slope and in the gallery, tiltmeters in the gallery, tacheometers and a new technique based on microwave radar (measures of distance from the opposite side of the valley: see Fig. 9.9), rain and snow gauges. Acoustic emission has been tested but did not give reliable results.

Some of these instruments are connected to an automated data recording and transmission system (33 extensometers, 54 distance measurements). Others are periodically surveyed, e.g. the geodetic measurements in the gallery.

The monitoring made it possible to define a zonation of the moving area (see § 9.3.4) and to make some inferences about the mechanism of deformation (see § 9.3.5.1): exclusion of simple

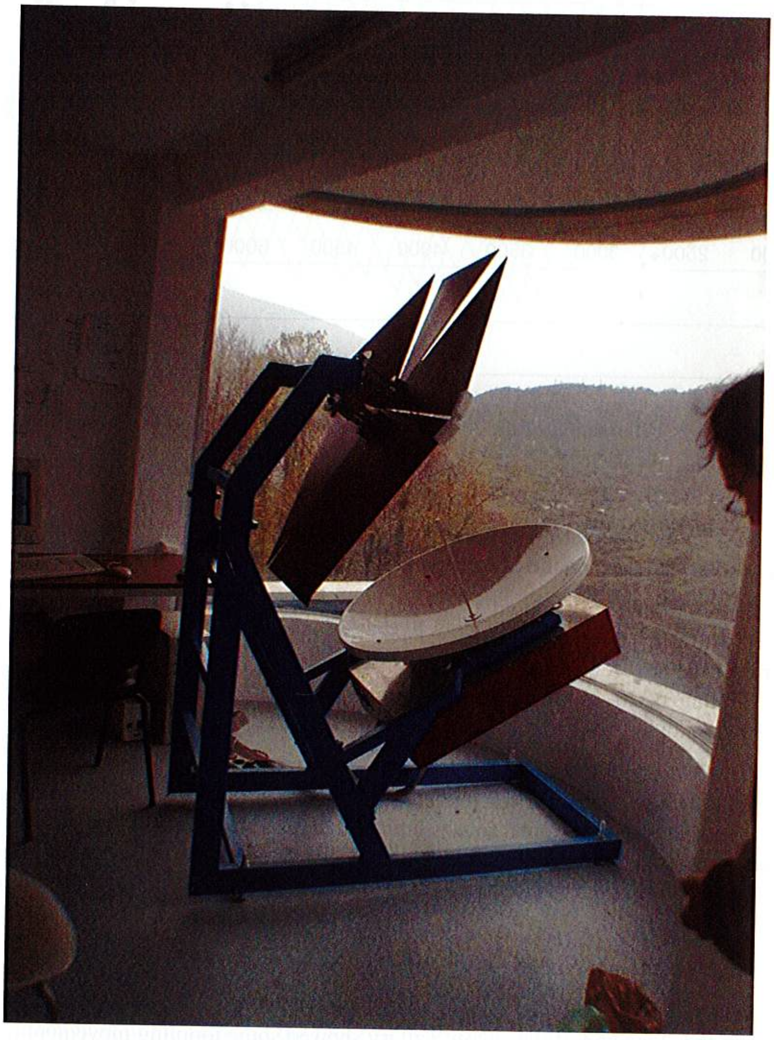

Figure 9.9. Microwave radar located on the opposite slope.

sliding on a plane or circular surface for instance, proposal of a complex deformation including some kind of toppling.

The history of the velocities measured by extensometer A 13 is shown in Figure 9.10. One can see, apart from the dispersion of values due to the actual accuracy of the extensometer, the large seasonal variations and a trend to increasing mean annual velocities.

Geophysical prospecting (electrical and seismic) has recently been performed by Grenoble University. The results are not yet completely available but it seems that the electrical and seismic properties of the rock are quite changed by the deformation process, in comparison to those of the intact formations.

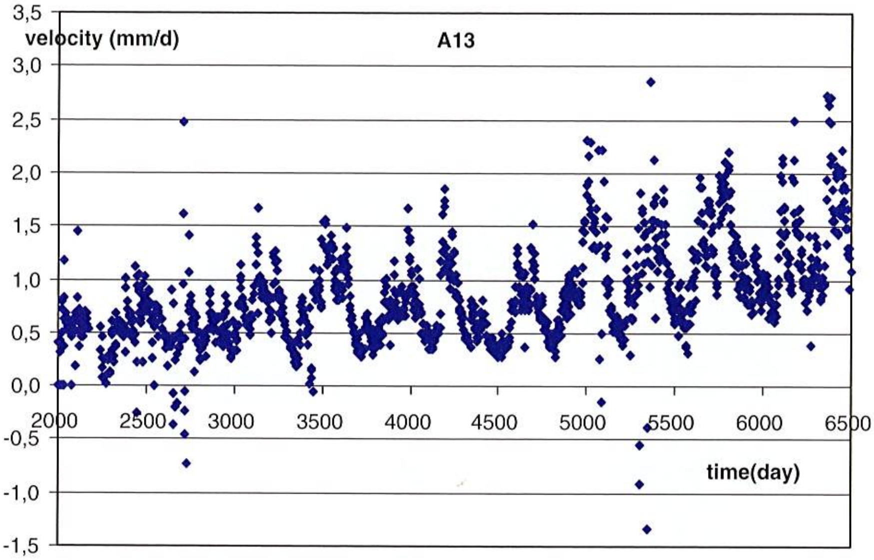

Figure 9.10. Rate of deformation of the A 13 extensometer (mm/day), located in the frontal zone. Day 2000 = 1990/12/05.

9.3.4 *Danger identification*

The hazard analysis is based on the existence of moving zones of various dimensions and velocities:

- the most active frontal zone (about 3 hm^3 with velocity of 0.15 to 1 m/y) periodically releases rockfalls (10–100 m^3) through Les Ruines; larger rockfalls (10^4 to more than 10^6 m^3) are expected to occur over the next few years,
- an active volume of 20–25 hm^3 (0.05–0.15 m/y),
- a large slowly moving zone (the ancient sagging): 0.02 to 0.04 m/y.

An important question is to know the volume of the frontal mass which could be destabilised in the short term. Many estimates have been made, ranging from 2 to 5 hm^3. In order to obtain the best estimate, it is assumed that the frontal zone is limited by a diamond-shaped polygon on the surface of the slope and by a basal surface dipping 30° towards the valley. This results in a volume of 3 hm^3.

This volume is used as a basis in the short-term reference scenario for the local authorities.

9.3.5 *Geomechanical modelling*

9.3.5.1 *Mechanical triggering model*

Monitoring of the slope and of the survey gallery showed some toppling movement of large rock masses. Numerical modelling with the distinct element method (DEM) yielded some interesting results despite the simplified 2D geometry and structure (only two families of discontinuities). It was shown that glacial melting induces slope deformation consisting of toppling in the middle of the slope, bulging of the lower part of the slope and sagging of the upper part, creating a major scarp at the top of the slope (Fig. 9.11).

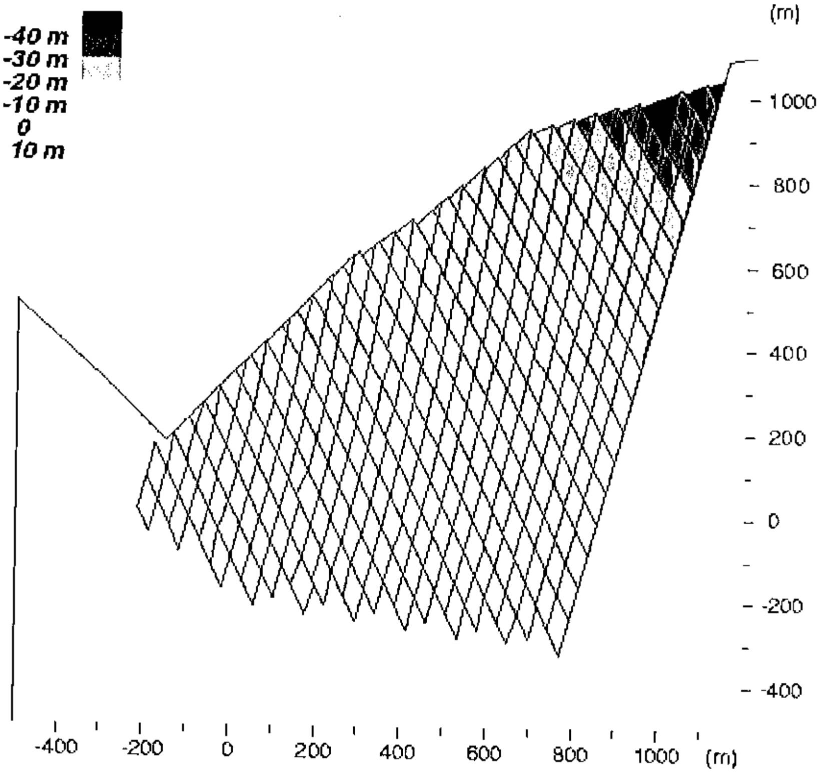

Figure 9.11. Vertical displacement as given by a DEM numerical analysis (UDEC code).

There is no need of a basal failure surface to obtain such deformations, which reflect the post-glacial evolution of the slope fairly well. But the reactivation of the deformation observed since about 1950 is not explained by this type of model, which stabilises after an equilibrium deformed state has been reached; new processes (weathering and fracture growth) must be added to the model to obtain the recent evolution. The present deformation combines some toppling of the frontal zone (increasing from west to east), which induces the deformation of the sagged upper part. The geodetic measurements in the survey gallery confirm the toppling movement of large rock masses separated by weathered clayey joints (Fig. 9.12). One can notice that the end of the gallery is not in the stable rock mass (it is moving slowly).

An empirical hydrogeological model has been proposed which makes it possible to find a relationship between the velocities of the frontal zone of day *n* and the water input (net rainfall and snow melting) of days $n - 1$, $n - 2$, etc. including 40 days of data. Recently, however, the reaction of the moving mass to precipitation seems to be quicker, probably due to the deformation process and increase in permeability.

9.3.5.2 *Mechanical run-out models*

Various numerical analyses have been performed with different hypotheses for the unstable volume. Due to the narrowness of the valley at the foot of Les Ruines, the river may be dammed if a 3 hm^3 failure volume is assumed (it may be noticed that the estimated volume of the frontal mass is about

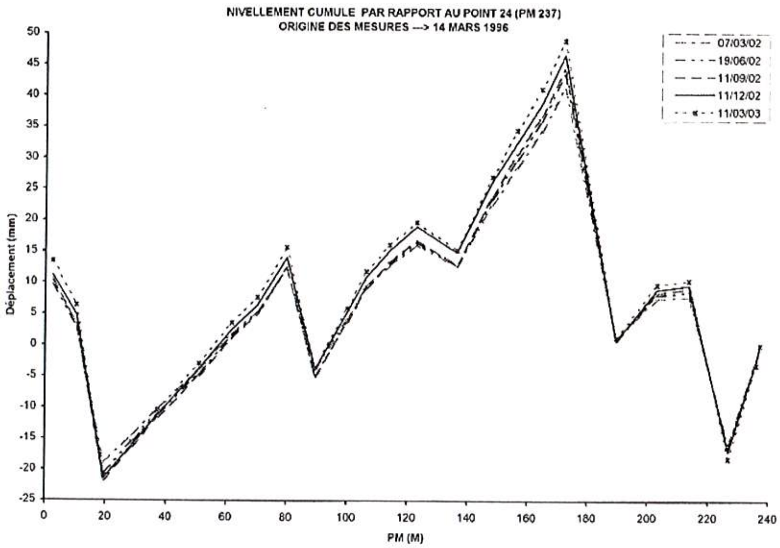

Figure 9.12. Vertical displacement (mm) along the survey gallery in relation to the end of the gallery (point 237 m on the right).

3 hm^3, i.e. around the threshold between damming and no damming of the Romanche valley!). Figure 9.13 shows the result of one run-out model, supposing that 3.2 hm^3 (4 hm^3 in the debris cone due to dilatancy) falls down in one step, a condition which strongly influences the shape of debris because of the increasing energy dissipation with volume (cf. the classical Heim or Scheidegger diagram of "Fahrböschung" versus volume); however, the model takes the progressive

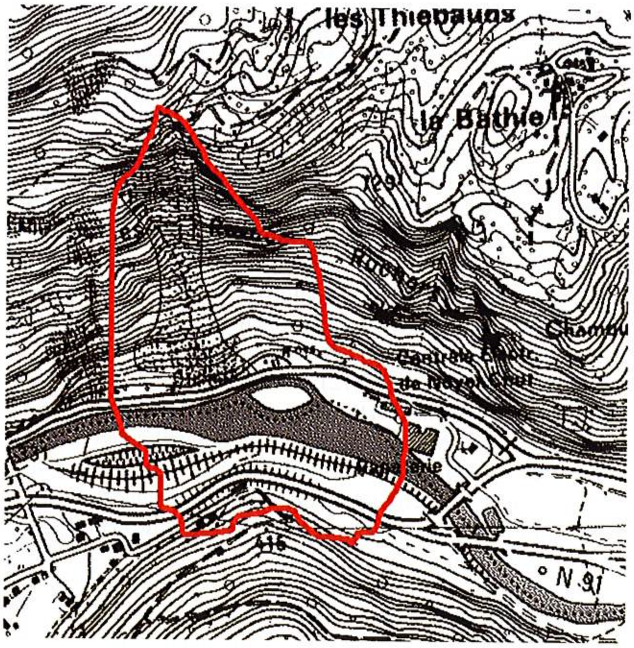

Figure 9.13. Extension of the debris in the case of 3.2 hm^3 failure volume (from R&R consultants): the valley is assumed to be completely dammed. Topography: IGN map.

change of topography during the spreading process into account. For larger volumes, the steep opposite slope will induce the diversion of the debris upstream in the Romanche valley (towards the village of Séchilienne) and downstream (towards Ile-Falcon).

Figure 9.14 shows another result for the spreading of the debris using a digital elevation model and a mechanical process with N = 1000 pieces of rock sliding one after the other, given a law of energy dissipation.

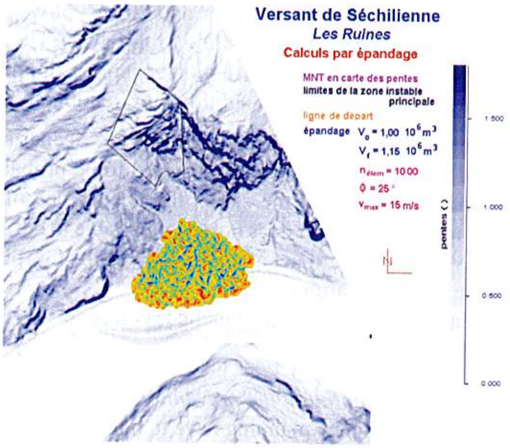

Figure 9.14. Debris cone resulting from a 1 hm^3 volume i.e., 1.15 hm^3 of debris simulation (courtesy of J.-F. Serratrice). It can be seen that the debris cone does not reach the earth protection dam in this case.

9.3.6 *Occurrence probability*

9.3.6.1 *Scenarios of rupture of the slope*

Different scenarios have been considered over the last years, including catastrophic failure of the whole landslide (nearly 100 hm^3). Two main groups of scenarios (in relation to the volume of rock involved) may be put forward at present, according to whether one considers the short term or the middle – long term (Panet et al., 2000). These groups have been defined in consideration of present scientific knowledge. They are based on physical considerations, such as measured velocities and opening of fractures.

- *Group 1* (short term i.e. <10 years): toppling and falls originating from the frontal zone; many rockfalls; failure of the whole frontal zone (about 3 hm^3), probably in several steps. There are two main possibilities: continuation of the current behaviour (rockfalls of a few cubic meters to hundreds or thousands of cubic meters) or a significant rockslide involving the whole fast-moving zone: the volume could be several million m^3 (2 to 3 in the more recent evaluation).
- *Group 2* (middle term: 10 to 50 years): the entire high or moderate velocity zone collapses. The volume could be 20 to 25 million cubic meters. Of course, intermediate scenarios could also occur.

9.3.6.2 *Consequences according to the volume of the rockslide*

In the same way as for the definition of the two groups of slope failure mechanisms, scenarios of the failure consequences may be defined according to the influence of the fall of debris in the bottom of the valley:

- *Scenario 1*: rockfalls of limited volume (e.g., less than 1 hm^3) do not dam the valley. The river will use the emergency riverbed. The debris cone does not reach or hardly reaches the RN 91.
- *Scenario 2*: a significant rockfall (3 hm^3) creates a small dam through the valley and a lake upstream. The dam is not very high (about 10 m) and the storage of water in the lake is about 200 000 m^3. A moderate volume of materials covers the RN 91.

- *Scenario 3*: a large rockslide occurs (about 5 hm^3) and creates a large dam (approximately 15 to 20 m). The water storage is about 3 million cubic meters. The filling rate of the reservoir depends heavily on the discharge of the river, and may last between one or two days and a few hours; the upstream village of Séchilienne is partly flooded. The overtopping of the dam can cause its own destruction and then generate a dramatic flood which reaches the town of Vizille in about ten minutes.
- *Scenario 4*: a catastrophic rockslide occurs (10–25 hm^3) and creates a very high dam (40 to 50 m). The reservoir (water storage between 10 hm^3 and 20 hm^3 of water) is filled within a few days (less than a day if it occurs during a rising period of the river). The village of Séchilienne is flooded. The overtopping of the dam and its destruction generate a dramatic flood, which reaches Vizille in about ten minutes and the industrial suburbs of Grenoble in 30–40 minutes.

Scenarios 1 and 2 are linked to the Group 1 slope behaviour. Scenarios 3 and 4 are related to Group 2. The occurrence of Scenarios 1 and 2 is considered to be probable in the next 10 years. Taking account of the current evolution of the slope, the occurrence of Scenario 3 is not considered to be realistic before about 10 years. It does not seem possible to define probabilities of failure for Scenario 4 because it is very difficult to get a precise idea of the morphology and of the hazard degree after a first rockslide involving around 3 hm^3.

The possibility of windblast due to the rock avalanche is controversial; in any case it would only be significant in the case of Scenario 4.

9.3.6.3 *Scenarios related to the planning of the prevention measures*

The authorities in charge of the emergency planning have to make a distinction between the following: closure or not of the RN 91, flooding or not of the plain upstream, flooding or not of Vizille, etc.

Many studies have been devoted to this subject. In particular, evaluations of the risk of flood downstream have been carried out with three values of water storage (3 million, 9 million and 20 million m^3).

From the knowledge of the slope and the results of these studies, various scenarios were defined. These scenarios make it possible to plan the actions of the authorities, either preventive ones (i.e., land use control) or curative ones (emergency plans). For each scenario, the authorities take into account a reasonably elevated evaluation of the risk, to guarantee a high level of safety, while not spending financial resources in a useless or premature way.

9.4 QUANTITATIVE RISK ANALYSIS

9.4.1 *Elements at risk*

The main elements at risk are, first, those affected by the run-out of the debris (hypothesis of 4 hm^3 or more): the RN 91 (nearly 10'000 vehicles/day, more than 20'000 during the winter holidays), the small village of Ile-Falcon (initially 90 houses), a paper factory (initially 51 employees) and a small electric power plant. Considering the importance of the risk to the people, in 1997, the French State decided to purchase all the installations directly threatened by the rockfalls. This operation is about to be completed at present (2003).

Other zones are exposed to secondary (indirect) phenomena, in the case of Scenarios 3 or 4:

- In the case of high damming and rising water behind the natural dam formed by the debris: flooding of the major part of the village of Séchilienne (670 inhabitants),
- In the case of overtopping and rapid erosion of the dam: flooding downstream in the Romanche valley affecting the town of Vizille and its surroundings (10'000 inhabitants) and chemical industries near Grenoble, etc.

Economic consequences could be very important if the road traffic is blocked because no other route of reasonable capacity exists during the winter. About 10'000 people live in the upper valley. The winter tourist activity of the ski resorts in the upper valley (Les Deux-Alpes, l'Alpe-d'Huez, etc.: 80'000 beds) provides an essential income to the regional economy.

There are also large economic consequences according to Scenarios 3 and 4 for the industrial facilities located downstream (chemical industries, electric power plant, etc.).

The environmental consequences could also be very heavy: 4 km downstream of Les Ruines there is a drinking water supply zone serving 200'000 people. This pumping area would be flooded in the case of Scenarios 3 and 4. There are also chemical industries downstream: these Seveso type industries could be hit by the flood in Scenario 4 and this could have a huge environmental impact.

According to the given scenarios, the following consequences may be considered:

Scenario 1: SMALL ROCKFALL (1 000 to 1 000 000 m^3)

This scenario may actually be considered as a non-event: it would (probably) be a first step – though already significant – which would not result in real consequences for property, as described in Table 9.1.

Table 9.1. Consequences of Scenario 1.

Romanche River	Cone scree reaches the river, likely locally diverting the flow towards the earth dam, inducing a beginning of diversion by the new bed. Pollution (suspended matter) of the Romanche River.
RN 91	Fall of blocks, temporary closure (several days); no significant damage.
Consequences downstream and upstream	Dust. Closure of short duration → economic impact on the ski resort of Oisans (80'000 tourist beds).

Scenario 2: ROCKFALL (3 million m^3) – SMALL DAM

Scenario resulting in a cone scree totally sealing the bed of the Romanche River and damming the valley at a moderate height. A lake of roughly 200'000 m^3 of water would form, as described in Table 9.2 (Fig. 9.15).

Table 9.2. Consequences of Scenario 2.

Romanche River	Temporary cut, diversion and divagation in Ile-Falcon, pollution (suspended matter).
RN 91	Road covered and destroyed (along about 80 m) by the rockfall. Closure of long duration (several months): significant economic impact on the ski resort of Oisans.
Inhabited zones upstream	Dust, etc. Possible evacuation during the crisis for the closest areas. No significant consequence.
Nearby downstream (1–2 km)	Approximately 1 km of road destroyed and a bridge damaged. Divagation of the Romanche river flowing out of the failure point in the dam.
Water supply of Jouchy	Possible effects on drinking water for 200'000 inhabitants.
Side dams in Romanche	Possible localised degradations, without overflow.
Inhabited zones downstream (2–5 km)	Dust, etc. Temporary increase in the flow of Romanche River, without significant consequence.
Other consequences	Possible damage to a small hydroelectric power plant. Damage to local power lines.

Scenario 3: ROCKSLIDE (5 million m^3) – MEDIUM SIZED DAM

Scenario with significant hydraulic risk of flood downstream (city of Vizille). Formation of an already high dam, with the creation of a significant lake (approximately 3 million m^3), as described in Table 9.3.

Note: The diversion tunnel now makes it possible to be protected against a failure of the dam if the discharge of the Romanche River remains low.

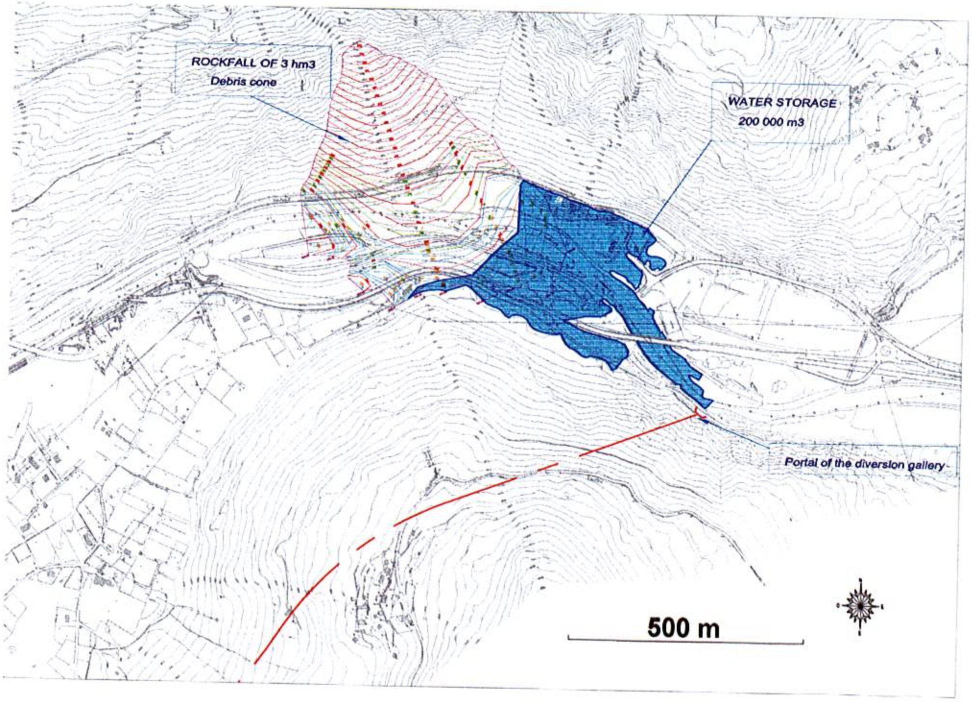

Figure 9.15. Lake formed in a 3 hm^3 rockfall hypothesis. See also the debris cone across the valley (see § 9.3.5.2), overflowing the catch dam, and the location of the eastern portal of the diversion gallery.

Table 9.3. Consequences of Scenario 3 (in case of dam failure).

Romanche River	Temporary cut, diversion and divagation in Ile-Falcon, important pollution (suspended solids).
RN 91	Road covered by the debris: about 150–200 m long and 15 m high. Closure of long duration (several months): significant economic impact on the ski resorts of the Oisans area.
Inhabited zones upstream	Dust, etc. Evacuation during the crisis (several weeks) for the closest sectors. Possibility of flood for some of the houses located at the lowest level.
Immediate downstream (1–2 km)	Approximately 1 km of road destroyed and a bridge destroyed. Divagation of the Romanche River, damping out the peak flow following the dam failure.
Water supply area of Jouchy	Pollution of drinking water for 200’000 inhabitants. Partial destruction of the pumping wells and pipes.
Side dams in Romanche River	Overflowed, destruction (4–5 km).
Inhabited zones downstream (2–5 km)	Dust, etc. Evacuation during the crisis (several weeks) for the closest areas: 5’000 to 15’000 inhabitants affected. Damage to numerous buildings (several hundred). Damage to roads, bridges (destruction) within a radius of 20 km (local or national level).
Other consequences	Possible damage to several hydroelectric power plants. Damage to local and regional power lines and other electric installations (30’000 inhabitants affected). Flood of chemical factories, risk of chemical pollution, cessation of activity for a long duration.

Scenario 4: ROCK AVALANCHE (20 million m^3) – HIGH DAM
The consequences of the failure of the dam are assumed to be very significant, not only within the close downstream valley (areas of Vizille and Jarrie), but also in the urban area of Grenoble. This means that more than 100'000 people would undergo damage due to a significant flood. Buildings, chemical factories, electric installations would be damaged or destroyed. Roads and motorways of national importance and railways would also be destroyed or damaged. The importance of the zone in question makes it difficult to define an exhaustive list of the potential consequences of this scenario.

This scenario highlights very heavy consequences. However, it is currently not considered to be possible for a long time (several decades), because of the need of undergoing several stages of deformation in the slope before it could occur.

9.4.2 *Vulnerability of the elements at risk and expected consequences*

Table 9.4 roughly shows the vulnerability of the main exposed elements for the various scenarios, as far as direct and immediate effects are concerned. The scale that is used is a relative scale and ranges from 0 to 100 (conventionally the value of 100 has been attributed to the catastrophic consequences of Scenario 4 in the Grenoble area). Finally, the table presents the situation as it was five years ago: today some preventive actions have already been implemented (see § 9.5).

Table 9.4. Vulnerability of elements at risk.

Element	Scenario 1	Scenario 2	Scenario 3	Scenario 4
National road RN 91 and other roads, railway	0,05	0,2	1	5
Upstream economic consequences	0,1	0,8	10	20
Upstream local consequences (flood)	0,05	0,2	0,5	5
Small village of Ile-Falcon (94 houses, 1 school, 1 restaurant)	0	0,5	2	2
Area of Vizille and surroundings	0	0,1	1	5
Local factories (a paper factory and a small hydroelectric power plant)	0	0,05	1	5
Water supply	0	0,2	1	5
Grenoble and surroundings	0	0	1	100

9.4.3 *Risk assessment*

No precise evaluation of the total cost of the scenarios has been made. One can roughly evaluate the cost of Scenario 3 at several hundreds of millions of euros.

One should also add that the social and economic impact already exists: the development of the Séchilienne village has been stopped and it is also probable that the chemical industries of Claix and Jarrie downstream in the Romanche valley are no longer investing at their sites. Moreover, large expenses have been devoted over the past twenty years to investigation and monitoring of the landslide.

9.5 REGULATION AND RISK MITIGATION MEASURES ALREADY AVAILABLE

Taking account of:

- the volume of rock material involved,
- the jointed nature of the rock mass,
- the hydrogeological complexity,

no stabilisation technique seems to be either technically or economically feasible. We can mention that even a solution of massive blasting has been assessed.

The new alignment of the RN 90 (which was initially located on the right side of the Romanche River) was opened in 1986; it has been diverted to the left side of the river and two new bridges had to be built. A diversion channel for the Romanche River has been prepared and is protected by a catch dam. It is supposed that these protective measures would be efficient for a failure situation involving not more than 1 or 2 hm^3 of rock.

The houses in Ile-Falcon have been removed and people (200) relocated in safe areas (Fig. 9.16). A factory has been closed. The government has purchased all these buildings from the private owners (cost: roughly 20 M€).

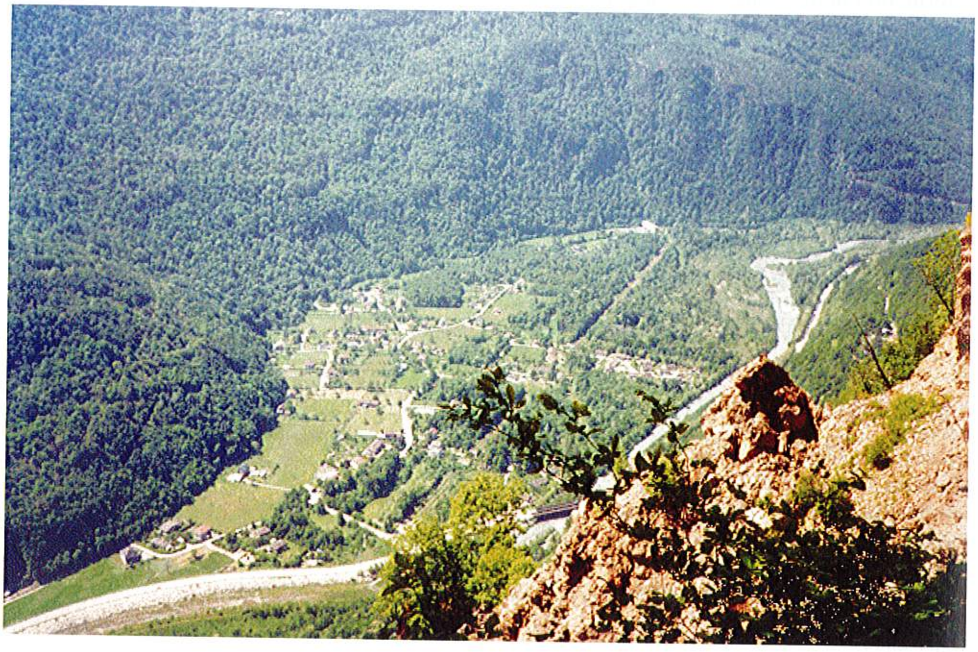

Figure 9.16. Ile-Falcon viewed from the frontal zone of Les Ruines.

A 2 km long exploration tunnel (Effendiantz et al., 2000) has recently been completed (10 M€); it was driven on the left side of the Romanche valley (see Figure 9.4). It could be used in case of catastrophic failure by the Romanche River but the discharge capacity ($60 m^3/s$) is only about a third of the maximum annual discharge. The need for a diversion suited to the floods of the Romanche River appears at the present time only for the scenarios likely to occur in the long run. One of the aims of monitoring is to determine the time when the implementing of this project would have to be decided.

The first emergency plan was worked out in 1993. A second version was prepared in 1999, corresponding to Scenario 3. Because of the recent analyses of the slope stability, and of the need for having an action plan adapted to the short term risks, a new version has recently been prepared. It corresponds to Scenarios 1 or 2.

Real time monitoring is a major component of this plan. Data from extensometers, distancemeters and rain and snow gauges are transmitted every 2 hours to the CETE in Lyon. In case of alert, safety measures would be progressively taken: closure of RN 91, call for the on site presence of experts, evacuation of people from the most dangerous zones, information for people living downstream, etc. The cost of monitoring is evaluated at 400 k€ per year (equipment value: 300–400 k€).

In the case of the occurrence of Scenario 1 or 2, the RN 91 would have to be reopened, probably after some clearing of debris and protective works. The main question would be to provide safe conditions for the workers and then to decide if the residual danger of rockfalls is over.

9.6 CONCLUSIONS

The Séchilienne and the La Clapière (Alpes-Maritimes) landslides are the two major active landslides in France. At both sites, the landslide risk has been efficiently managed for more than s25 years, in spite of all imaginable types of difficulties. This has represented a scientific challenge as much as a political and financial headache...

Our knowledge of these large slope deformations is rather poor, therefore, there is no certain prediction of the future evolution of the system: the best approach is the construction of scenarios, the assessment and evaluation of these scenarios and their continuous updating in order that the local and regional authorities may take appropriate preventive measures and organise the preparedness in the manner most suited to the situation.

The history of Les Ruines de Séchilienne has not yet come to its end. The scientific experts have sometimes been mistaken, but the observations and data collected from the site allow continual understanding of the phenomenon and our ability to define the most probable scenarios, and therefore to prepare the mitigation decisions which are the responsibility of the political authorities.