Vulnerability and risk assessment of a mountain road crossing landslides

Erika Prina,* Christophe Bonnard,** Laurent Vulliet**

Summary

Risks of natural disasters are steadily increasing, dùe mainly to the growing exposure of goods and population to wide range of hazards, as well as to possible side effects related to global warming. After a brief introduction on the importance of natural catastrophes worldwide and to the question of integral risk management, the paper focuses on a case study.

In the western part of Switzerland, an important mountain road connecting the town of Aigle to the village of l'Etivaz, over some 25 km and passing by the Col des Mosses pass (El. 1.445 m), is threatened by many natural dangers, among which the well known slides of La Frasse and La Lécherette which have experienced crises in the past. In other areas, hazards of rockfall, partially controlled, of debris flows and of avalanches also exist.

In order to take appropriate preventive measures and avoid thus that these dangers turn out into catastrophes, it is first necessary to carry out a complete assessment of the risks induced by the road. Several steps will be followed. The first step includes the knowledge of the natural phenomena, i.e. localisation, limits, geological and morphological conditions, actual activity, data on past events, in order to prepare maps of phenomena. The second step leads to class the potential dangers or hazards into three categories (low, medium and high hazard) and to produce danger maps. The third step relates to vulnerability analysis and the fourth step to the risk assessment.

The study has led to fix a degree of risk rated from 0 to 4 for each 250 m unit stretch of the road.

1. Introduction

Risk management will certainly become a major issue in the domain of natural hazards, to protect major routes for example. Well established in the technical fields (aerospace, nuclear energy, chemical engineering, etc), the risk analysis and risk management methods are only starting to be applied/developed for natural hazards. Among other reasons for this late interest, we can mention (i) the complexity of the involved system (including stakeholders), (ii) the strong interactions between various (heterogeneous) phenomena, (iii) the difficulty in modeling the physics of the phenomena and predicting their probability of occurrence, (iv) the "prototype" nature of each individual event (preventing to express a statistical "mean time to failure" similar to an industrial component), (v) the difficulty in evaluating the consequences (economic, social, environmental) of a natural physical hazard.

It is an established fact that natural disasters are much more damaging than industrial ones. As an example, for the year 1999, 105.000 casualties resulted from natural hazards worldwide while "only" 7.000 were caused by technical reasons (data from Swiss Re – Swiss Reinsurance Company). In terms of insured damage, the ratio is 25 vs. 4 billion US$ for that same year (noting in particular that insured damage does not include damage in most of the -uninsured- developing countries). Furthermore, the number of major natural disasters of any kind is steadily increasing (see Fig. 1), mainly due to the increase of exposed goods and the population growth. As a consequence, most of the nations are setting interdisciplinary teams at various strategic or operational levels to cope with natural hazards.

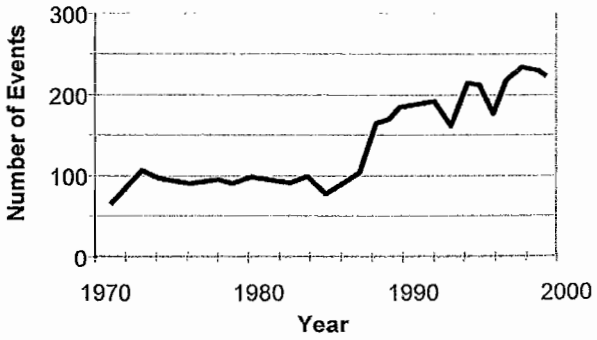


Fig. 1 – Number of events inducing major natural disasters with time (Data from Swiss Re).
Fig. 1 – Numero di eventi che inducono a dei principali disastri naturali nel corso del tempo (Dati da Swiss Re).

* Soil Mechanics Laboratory; Swiss Federal Institute of Technology, Lausanne, Switzerland
Now at Géotechnique Appliquée Dériaz SA, Mont-sur-Lausanne, Switzerland
** Soil Mechanics Laboratory; Swiss Federal Institute of Technology, Lausanne, Switzerland

An appropriate integral risk management approach must consider all phenomena (which is usually not the case as, historically, a sectorial approach is prevailing in most countries) and is composed of several topics (see Fig. 2):

- Risk analysis and assessment (hazard and vulnerability analysis);
- Risk appraisal and evaluation (human condition and culture, subjective evaluation, risk acceptability);
- Risk reduction strategies (prevention and event preparedness);
- Event management (response mechanisms, emergency infrastructure).

The aim of this paper is to address and illustrate a part of these points by means of a real case study. It will focus on a geographically well-defined area: a 25 km long road in a Swiss alpine region. The system is restricted to the road, and the surrounding areas are only considered as external input to the system. A description of the problem and the risk assessment procedure will be given first. The hazard potential will then be discussed. A vulnerability study and the resulting risk analysis will lead to propose several risk reduction strategies.

2. Presentation of the studied road from Aigle to l'Etivaz

2.1. *Location*

The studied stretch of route is an important mountain road, classified as 1st category cantonal road (RC 705a) which connects the town of Aigle, located in the Rhone valley not far from the lake of Geneva, where the A9 motorway passes, to the village of l'Etivaz which is a part of the Commune of Château-d'Oex in the Prealps of the Canton of Vaud (Switzerland). This road leads then to Gstaad and several tourist resorts of the Berner Oberland. Displaying a total length of some 25 km, it passes by the "Col des Mosses" Pass at El. 1.445 m, as well as by other small villages or specific points which are mentioned with their elevation in Table I (see Fig. 3).

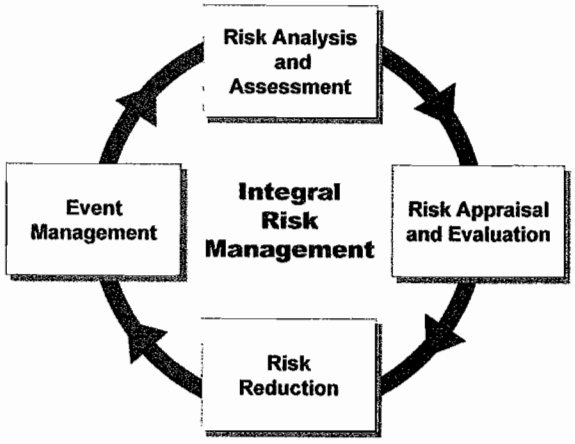


Fig. 2 – Components of integral risk management.
Fig. 2 – Componenti della gestione globale del rischio.

Near the Col des Mosses, the surrounding peaks, namely the Pic Chaussy and the Mont d'Or, reach elevations of respectively 2.350 and 2.175 m a.s.l. On most of its length, the road has a standard width of 6.0 m and its pavement is well maintained, so that the cars that constitute the major portion of the traffic drive fairly fast, despite of the slopes which vary generally between 4 and 8%.

2.2. *Economic significance*

As shown in Table I, this road has a major touristic function as it allows the access to the resorts of Leysin, Col des Mosses, Les Diablerets, and further Château-d'Oex and Gstaad. It is the shorter route between the Canton of Valais and The Berner Oberland. In order to determine the importance of the touristic activity in relation with this road, the development plans of the three directly concerned communes, namely Aigle, Ormont-Dessous and Château-d'Oex have been examined; for instance the hotel occupation in the concerned area means more than 310.000 nights in winter and more than 260.000 in summer. It is thus important to guarantee an easy and safe access to the touristic resorts.

Furthermore this road is also used for the transport of all local products, in particular the wood logs

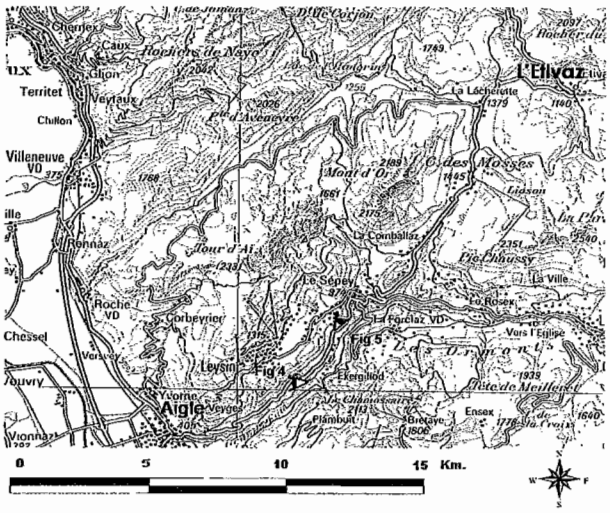


Fig. 3 – Topographic map of Aigle-L'Etivaz road in the Prealps of the Canton of Vaud, Switzerland, with location of sites shown in the following figures.
Fig. 3 – Mappa topografica della strada Aigle-L'Etivaz nelle Prealpi del cantone Vaud, Svizzera, con l'indicazione dei siti mostrati nelle figure seguenti.

Tab. I – Main locations and elevations along the studied road.
Tab. I – Principali località e quote lungo la strada studiata.

Location	Distance from Aigle [km]	Elevation (m a.s.l.)	Observation
Aigle	0	427	Town of approx. 7.500 inhab.
Le Sépey	10.0	1.000	Crossroad to Leysin touristic resort
La Crête	11.5	1.078	Crossroad to Les Diablerets touristic resort
Col des Mosses	18.0	1.445	Highest elevation; touristic resort
La Lécherette	20.5	1.379	Touristic resort; access to the Hongrin dam
L'Etivaz	24.5	1.140	End of studied road

and the cheese (L'Etivaz is one of the largest refinement centers for the Gruyère cheese produced in the area).

The traffic in Aigle, at the beginning of the road, has substantially increased during the last 20 years, especially in the eighties, passing from an average daily value of 3.500 vehicles in 1980 to 5.000 in 1993.

2.3. *Geological and hydrogeological setting*

The region called "Alpes Vaudoises" in which the studied road extends is geologically constituted of a part of the Medium Prealps that are formed by plastic to rigid superimposed nappes which have passed over the Alps from Northern Italy. The types of rocks encountered in these nappes are dolomites, breccia, gypsum of Triassic age and marls, silty schists and massive limestones of Jurassic age, as well as Flysch formations. In some areas these rocks are covered by local moraines and detritic deposits.

These rocks can be characterized by some specific features:

- the gypsum and the limestone are subject to karstic phenomena;
- the marls and silty schists are quite impervious;
- the flysch, that is fairly impervious, is frequently associated with slides and debris flows;
- the detritic deposits are often fairly pervious and display a low cohesion.

As far as hydrogeological conditions are concerned, the karstic limestones forming the mountains to the west of the road are characterized by important underground flows leading to abundant springs in the vicinity of Aigle; but these flows do not seem to have any relations with the seepage flows that affect the more impervious material forming most of the unstable slopes [BONNARD *et al.*, 1987].

2.4. *Typical landslide and other dangerous phenomena met along the road*

A detailed study on all the investigation works carried out in the area surrounding the road Aigle-L'Etivaz leads to identify the following dangers that may affect it:

- Rockfall, in particular near Aigle and in Les Grands Rochers cliff, where protection galleries have been built (see Fig. 4);
- Large slides, in particular La Frasse (see Fig. 5) and La Lécherette landslides;
- Debris flows in several streams or torrents near Aigle, Le Sépey and L'Etivaz;
- Dolinas and flows related to karstic phenomena, in particular near Aigle and La Lécherette;
- Snow avalanches, in particular the one descending from the Pic Chaussy;
- Floods, at the very beginning of the road where it crosses the Grande Eau River at Aigle, as well as at the point where La Frasse Landslide toe reaches this river (risk of dam break), and at the

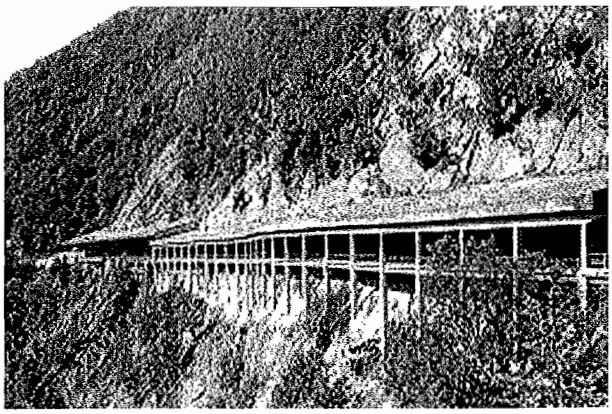


Fig. 4 – Protection galleries along the Aigle-L'Etivaz road, in the Grands Rochers zone, preventing the traffic from rockfall.
Fig. 4 – Gallerie di protezione lungo la strada Aigle-L'Etivaz, nella zona Grands Rochers, che proteggono il traffico dalla caduta di massi.

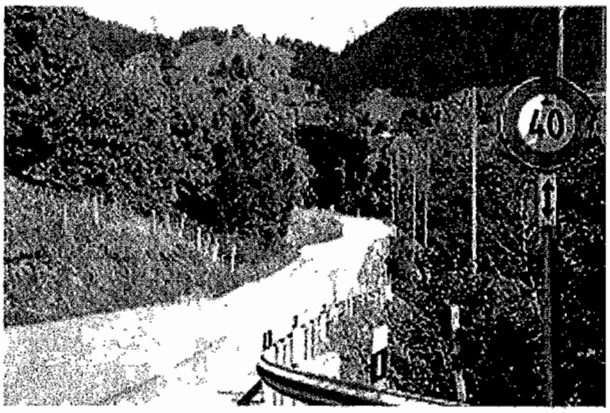


Fig. 5 – Visible deformation of the road where it crosses La Frasse Landslide which displays a high velocity in this stretch, reducing thus the safety of the traffic.
Fig. 5 – Visibile deformazione della strada che incrocia la frana La Frasse che mostra un'elevata velocità nell'allungamento, riducendo così la sicurezza del traffico.

very end of the road where it crosses the Eau Froide River at L'Etivaz.

It may be already mentioned that the road which was built 170 years ago was sometimes affected and blocked for a short period of one day or two by one or the other of the phenomena mentioned above, but was never destroyed or impossible to use for long periods of several weeks, even during the crisis of La Frasse Landslide in the winter 1981-82, when the total displacement reached some 4 m.

3. Risk assessment procedure

The risk assessment, the final objective of which is to prevent natural disasters, aims at better protecting and managing the land and elements exposed to various natural dangers. Such an analysis requires a systematic procedure presented in the scheme in Figure 6, which is inspired from Varnes [VARNES, 1984].

The procedure adopted consists in four stages:

- The first stage implies the creation of an operational data bank including relevant information on all natural phenomena (see § 4.1) which may affect the endangered elements (maps of phenomena, data on intensity, probability and combination of possible mechanisms). This data bank also includes information on the elements, in a general sense, which may be exposed to the corresponding hazards, both in terms of sensitivity or vulnerability and in terms of costs or value. These elements include physical objects, human life, environmental aspects and economic activities that are indirectly affected.

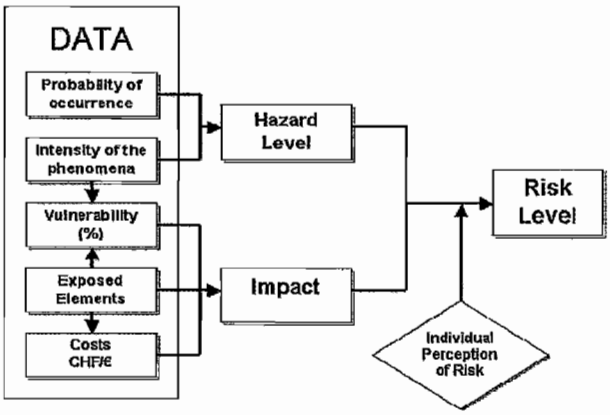


Fig. 6 – General scheme applied to assess the risks.
Fig. 6 – Schema generale applicato alla valutazione del rischio.

- In the second stage, the assessment of the hazard induced by the natural phenomena, as well as their secondary consequences, must lead to express classes of potential of danger for each different type of phenomenon and for each spatial part of the exposed zone (see § 4.2-4.3).
- These hazards may cause a certain impact on the exposed elements in these zones which can be measured in a third stage, in monetary value or by different indicators (for instance to avoid the monetary expression of life), and depend on their respective vulnerability (see § 5).
- Finally the combination of hazard and impact allows the expression of a risk level in the fourth stage, expressed in general in terms of classes, as the monetary expression is not significant for the population (see § 6). These classes may be affected by the individual or societal perception of risk which is variable according to the sensibility of the population to natural phenomena, as well as to the possible occurrence of large disasters (aversion factor).

The determination of risks is useful to orientate preventive actions like installing monitoring tools, carrying out typical protection measures or evacuating exposed zones, so as to adopt means that are justified on the technical, economic and social points of view. The final result of this analysis will thus be a risk map corresponding to the studied road which has to be easily readable and divided in unit stretches of route.

4. Hazard assessment

4.1. Identification of phenomena

In order to assess the hazard to which the considered road is exposed, it is first necessary to identify the natural dangers of all kinds mentioned

in § 2.4, which affect or may affect it. In this phase all the information supplied by geological, morphological, historical studies, as well as by previous specific mappings of the phenomena integrating the traces left in the field by past events, are considered (see Fig. 7).

Then the potential evolution of a natural phenomenon into a danger is assessed considering its basic predispositions to present a critical behaviour (like the low shear strength characteristics of the material in the slip surface of a slide or the degree of facturing of a rock cliff), its variable predispositions to experience a crisis (in relation with extreme meteorological conditions, for example) and the triggering factors that may induce a sudden acceleration (like an earthquake). The analysis of these three factors, as well as the past events, will lead to the formulation of relations between the frequency and the intensity of disasters or exceptional behaviours.

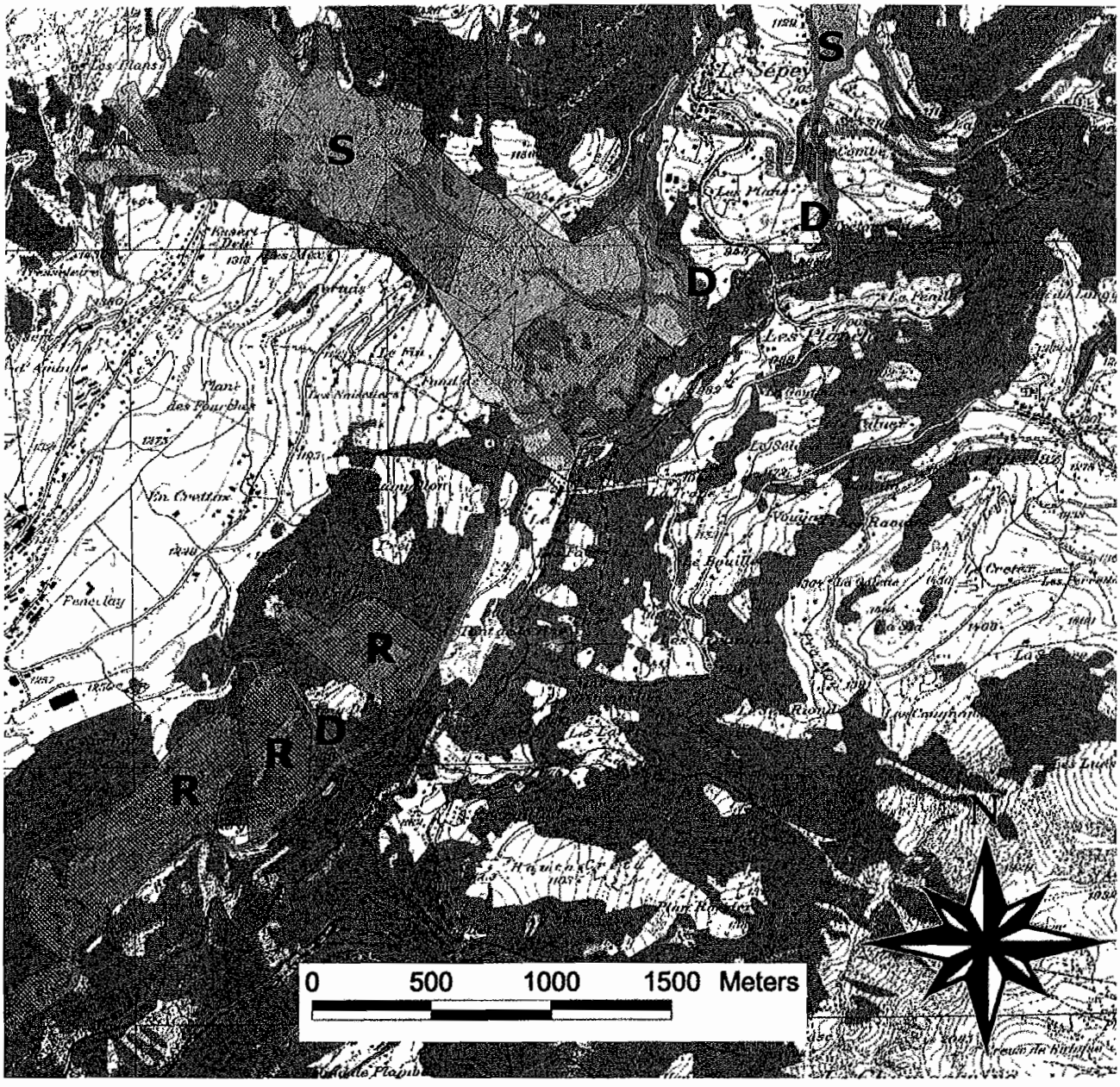


Fig. 7 – Synthetic map of observed natural phenomena: slides (S), rockfall (R), debris flows (D) affecting a part of Aigle-L'Etivaz road, including in particular La Frasse Landslide. All the information was gathered in different sets of maps for the relevant phenomena.

Fig. 7 – Mappa riassuntiva dei fenomeni naturali osservati: frane (S), caduta massi (R), colate detritiche (debris flow) (D) che interessano una parte della strada Aigle-L'Etivaz, includendo in particolare la frana La Frasse. Tutte le informazioni sono state prese in differenti gruppi tematici di carte.

4.2. *Hazard level*

In order to elaborate a hazard map for each specific phenomenon, it is necessary to assess the possible intensity (or intensities) of the natural phenomena, as well as the probability of occurrence of an event of any intensity. These two sets of parameters will then be combined in a matrix form, as shown in Figure 8, in order to fix the relevant hazard level [OFAT; OFEE; OFEFP; 1997]. An assessment of these parameters cannot be formulated mathematically through equations.

Indeed three levels are defined in the Swiss recommendations, as far as intensity is concerned, with respect to the effects that the considered danger is liable to induce on the exposed objects:

- Level 1: For low intensity, men and animals are hardly threatened even outside of the buildings, except in case of isolated small block fall for which an exceptional lethal danger may always exist. Buildings and infrastructures may present some minor damage or deformation which do not affect their integrity.
- Level 2: For medium intensity, men and animals may be seriously threatened if they are outside. Buildings and infrastructures present limited damage, but their global stability is ensured and they are easily repaired.
- Level 3: For high intensity, men and animals are threatened even inside of their dwellings. Buildings and infrastructures suffer serious damage which may lead to their complete destruction, for instance due to severe differential settlements.

As far as the probability of occurrence is concerned, it is generally related to the return period of the phenomenon, assessed on historical data or conditional probabilities.

4.2.1. *Slides*

The qualification of slide hazard depends first on two parameters:

- their long-term average velocity, which expresses a degree of activity and thus qualifies their intensity (for instance velocity v > 10 cm/year corresponds to high intensity).
- their maximum depth with respect to the main slip surface, which allows an assessment of the volume of the moving mass, provided its spatial extension is known.

Furthermore, two other criteria must be considered:

- only some slides display a high potential of acceleration, in general due to hydrogeological conditions, whereas the majority of slides are affected by a more or less continuous movement which impedes to introduce the notion of probability of occurrence; in this case the intensity alone will fix the hazard level [LALOUI *et al.*, 2004; BONNARD, 2004];
- the zones close to the limits of slides or displaying differential movements are affected by a higher hazard potential than the zones in the middle of the moving mass [OFAT; OFEE; OFEFP; 1997].

Finally the conjunction of main and secondary slides must be considered in the hazard level, as well as the interaction of the toe of the slide with an adjacent river. Thanks to a large amount of previous studies (in particular [NOVERRAZ *et al.*, 1993; NOVERRAZ, 1994; BONNARD, 1983; NOVERRAZ *et al.*, 1998]), it has been possible to precisely state the hazard level along the road between Aigle and l'Etivaz. In particular, this road crosses two main slides, namely La Frasse and La Lécherette, which both display a maximum hazard level of three, corresponding to a high velocity (v > 10 cm/year) and a high depth (h > 10 m). Apart from these two main sites, 18 other slides with a smaller extent have been considered.

4.2.2. *Dolinas*

Due to the presence of Trias formations near the surface, like gypsum and limestones, karstic phenomena are present in the studied area and are visible by the presence of several dolinas, the spatial density of which is an indicator of such hazard. Some sudden outburst of flow from springs connected to the karstic limestone massif which dominates the area are also characteristic of this hazard.

For such phenomena displaying a slow and continuous dissolution mechanism, it is not possible to express a probability of occurrence even if sudden subsidence phenomena may occur from time to time. The criteria of hazard intensity is thus related to the presence of dolinas encountered in some zones (hazard level 2) and to the distance from these dolinas to the studied road (high hazard level if the distance is less than 20 m) [BOSSY, 1999].

4.2.3. *Snow avalanches*

In order to state the hazard level of an avalanche, it is necessary to determine first the historical events in the region and the possible extension of their impact, depending of the type of mechanism, site of triggering, type of slope, vegetation cover and stratigraphy of deposited snow. In the case of powder snow avalanches, the velocity of the phenomenon may sometimes reach 30-100 m/s.

Several methods have been developed to assess their hazard level as a function of the return period, as well as the pressure they will induce on structures, which allows the definition of high, medium and low

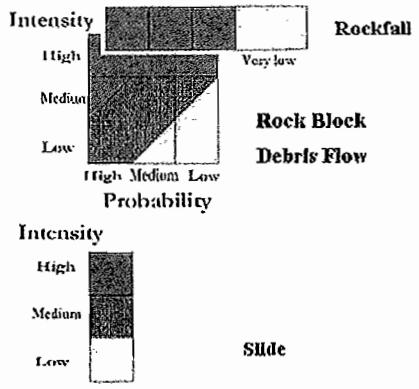
danger zones. Other more simple methods like the French CLPA one (Carte de localization probable des avalanches) allowed the determination of the endangered zones along the road from Aigle to L'Etivaz. Two zones at the foot of Le Mont d'Or and Pic Chaussy mountains display a hazard level of 2 (medium hazard) affecting a short stretch of the road [BARDOU, 2000].

4.2.4. *Rockfall*

This type of phenomenon includes a very variable volume of rock material susceptible to fall from cliffs above the studied road. The intensity classes can be fixed, according to the Swiss federal recommendations [OFAT; OFEE; OFEFP; 1997] by the consideration of energy values, E, namely:

Low intensity: $E < 30$ kJ
Medium intensity: $30 < E < 300$ kJ
High intensity $E > 300$ kJ

These values refer to the resistance of a rigid wooden barrier (30 kJ), respectively a well designed reinforced concrete wall (300 kJ). The corresponding hazard matrix combining intensity and probability is shown in Figure 8. The lower limit of the high probability class, respectively the lower limit at the low probability class, are suggested as 30 and 300 years, by reference to the federal recommendation relating to avalanches.



Note : For permanent landslides, no probability assessment is required.

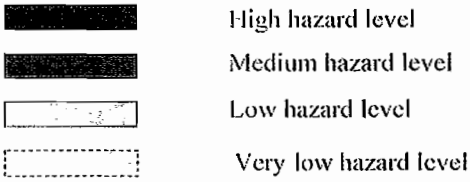


Fig. 8 – General matrix representation of the relations between intensity and probability to qualify the hazard level [OFAT, OFEE, OFEFP, 1997].
Fig. 8 – Matrice generale di rappresentazione delle relazioni tra l'intensità e la probabilità per qualificare il livello di pericolosità [OFAT, OFEE, OFEFP, 1997].

In the case of the studied road, the zones of rockfall are fairly numerous, i.e. 21 recognized sites, with half of them displaying a high hazard level. One of the major ones, as shown in Figure 4, at Les Grands Rochers, and on the map in Figure 7, is already protected by two different reinforced concrete structures built first in the years 1960 (shed with columns) and then in the years 1980 (unsupported shed with prestressed cables). Indeed a short stretch of high hazard still exists, just at the upper limit of this protection work, where a large block fell some years ago on the road. In all the considered sites, the volumes liable to fall are limited (for one third of them, between 4 and 15 m^3), but the height of fall is often higher then 50 m (in two thirds of the cases) on a very inclined slope (in most of the cases above 40°), with only limited vegetation which could reduce the kinetic energy at the road level. Therefore a high intensity is considered in nearly all exposed zones.

4.2.5. *Debris flows*

Several small streams intercept the studied road, but most of them flow down very steep slopes and cross zones of weathered rock or clayey moraine and alluvial deposits, so that a possibility of debris flow or mud flow has been identified in 15 sites and confirmed in most cases by historical events. In order to assess their potential intensity, the Swiss federal recommendations already mentioned have been followed, considering either the observed height of deposited material along the stream (high intensity if $h > 1$ m), or the potential depth of erodable material in the slopes (high intensity if $e > 2$ m, for instance). In the studied cases, half of them display a high hazard level of 3 and the other half a medium hazard level of 2 (see one of them in Fig. 9). Indeed the probability of occurrence is strictly related to the specific meteorological conditions in the zone, but up to now no extraordinary debris flow has been recorded in the past.

4.2.6. *Floods*

The studied road avoids the bottom of the valley in which floods might occur except at the very beginning (km 0) in Aigle, where it crosses the Grande Eau river, and at its very end, at l'Etivaz, where it crosses the Torneresse river.

In these two points no static flood may occur implying a slow increase of water level higher then the road, but a major flow of these mountainous rivers is possible; in 1968 a flow of 81 m^3/s occurred which is nearly the centennial flood (85 m^3/s according to a Gumbel distribution). The flow capacity below the bridge at Aigle is assessed to be 110 m^3/s, but a cer-

tain amount of sediments and trees in the flow may easily cause an overflow.

Such a hazard for the studied road is thus reduced and has not been taken into account. However, in a more detailed analysis of the potential consequences of the damming of the Grand Eau river by the lower part of La Frasse Landslide, shown in pink (see Fig. 7), a much violent flow might be expected as a very rare event, inducing major damaging consequences. Therefore, the situation of the bridge at Aigle will deserve special attention in the risk analysis.

4.3. Hazard maps

In order to gather all the available information related to the various natural dangers considered, a GIS data bank has been set up, representing first the zones exposed to these dangers at a scale 1:25.000. Thus 4 maps for rockfall, 4 maps for slides, 3 maps for debris flows and one map for snow avalanches have been prepared (see Fig. 7 superposing three specific maps of phenomena for a stretch of road near La Frasse Landslide). Several points have needed local field controls to check the reliability of the available documents and their present validity. The interaction between two phenomena at a same location is not specifically mentioned, but will be analysed in the risk assessment process. In the same way, the presence of protection works will modify the risk level.

Then hazard maps have been established, considering the matrix given in Figure 8, which has lead to the production of 12 maps (see Fig. 9 superposing three specific hazard maps for the final stretch of road near L'Etivaz).

The hazard level provided is thus partly qualitative, but allows a homogeneous consideration of all dangerous phenomena.

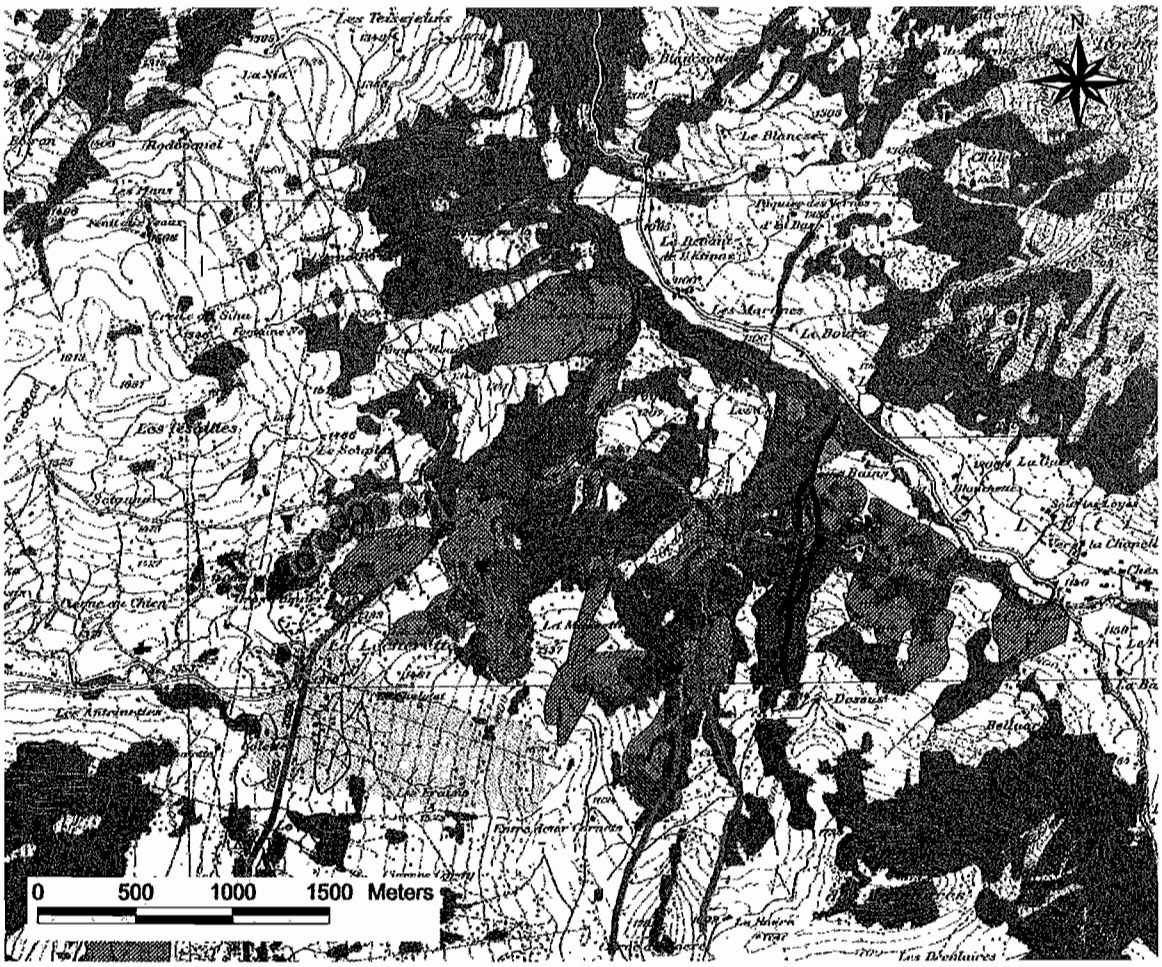


Fig. 9 – Hazard map expressing the hazard level along the final stretch of Aigle-L'Etivaz road, due to slides, debris flows and dolinas (red dots). The hazard is expressed by three levels, namely yellow (low value), blue (medium value) and red (high value).

Fig. 9 – Mappa della pericolosità che evidenzia il livello di pericolosità lungo l'allungamento finale della strada Aigle-L'Etivaz dovuto alle frane, debris flows e doline (puntini rossi). Il rischio è espresso da tre livelli, nominalmente il giallo (basso valore), il blu (valore medio) e il rosso (valore elevato).

5. Impact assessment

5.1. Vulnerability

According to the definition expressed by VARNES in 1984 [TURNER & SCHUSTER, 1996], the vulnerability factor considered in the theoretical risk equation means the degree of loss or potential damage to a given element (or set of elements) at risk resulting from the occurrence of a natural phenomenon of a given probability and magnitude, over a certain spatial extent. Indeed this factor is not unique, as it depends mainly on the intensity of the hazard, on the type and sensitivity of exposed objects (in a wide sense) and on the perspective regarding the nature of the loss. This last aspect leads to express four partial vulnerability factors, namely:

- physical vulnerability with respect to direct danger to buildings, structures, infrastructures, networks and objects;
- social vulnerability, with respect to direct impact on life, physical and mental health and living conditions (loss of home, evacuation);
- environmental vulnerability, with respect to direct impact on natural environment (forests, animals, plants, water, etc.) considering their short and long term sensitivity;
- economic vulnerability, with respect to indirect impact of the phenomenon on various activities that are affected by the hindrances induced (paralysed traffic, reduced touristic demand, longer travel distances for industrial goods, loss of values of adjacent plots of land, etc.).

At a given point of a landslide or on a considered infrastructure like the road analysed in this paper, the four components of the vulnerability factor can be represented synthetically as shown in Figure 10. Thus each component may vary between 0 (no impact) and 100% (total destruction).

In order to determine the values of the vulnerability factors, it is necessary to understand the behaviour of the landslides as well as the interaction between the phenomena and their damaging effects on the exposed elements. In the case of slides, no global computation model exists to determine such value, as the relevant phenomena display quite variable characteristics and as the damage is often improperly monitored and reported. The four partial vulnerability factors are governed by the following principles:

- As far as physical damage is concerned, it must be assessed in terms of structural failure, but also in terms of operational failure, for instance when the tilting of a house or a road exceeds an acceptable value, even though no cracks are reported. It also depends on the building materials used and on the maintenance of the structures.
- Social vulnerability can also be conditioned by the capacity of the population to anticipate the threatening phenomenon and its ability to prevent any excessive exposure (spontaneous evacuation, preventive measures carried out).
- Two main aspects of the environmental vulnerability depend on one hand on the presence of protective forests against rockfall which may induce major damage if they are affected by the movement of a slide and on the other hand on the possibility of damming a stream which may then induce flooding upstream and downstream, if the natural dam caused by the slide breaks. This last situation may also be called secondary vulnerability, and requires to extend the investigated zone much further than the zone strictly exposed to the original landslide.

Thus for each type of vulnerability factor, as well as each type of landslide, a matrix can be determined as a function of the intensity of the phenomenon and of the type of exposed objects. Several assessed values for these vulnerability coefficients have been proposed, for instance by Leone [LEONE *et al.*, 1996]. In our case, dealing mainly with a mountain road, two aspects are predominant in the vulnerability assessment:

- the road structure itself, and in particular its potential deformability in the zones where it crosses active slides (see for example Fig. 5);
- the traffic on the road including vehicles and persons that are exposed to rockfall or debris flows.

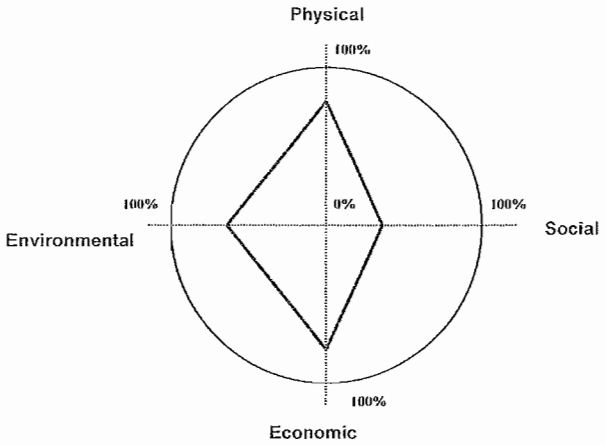


Fig. 10 – Schematic representation of partial vulnerability factors at one point where damage may occur, due to any natural hazard.

Fig. 10 - Rappresentazione schematica dei fattori di vulnerabilità parziale nel punto in cui accade il danno, dovuto a qualsiasi pericolo naturale.

Both factors have been assessed by matrices as a function of the intensity of the hazard. For instance, an irregular road surface is qualified by a factor varying between 0.1 and 0.3 according to the state of the road, whereas a failure of the road platform or its obstruction is qualified by a factor of 0.8 to 1 according to the seriousness of the damage. A vehicle hit by a stone, but not seriously damaged induces a factor of 0.1 to 0.2, but this value may reach 0.9 to 1 if the vehicle cannot be repaired. Finally, the persons exposed to rockfall, even of limited volumes, induce a social vulnerability of 1 as the impact of a stone may be lethal, as it was frequently observed.

5.2. Impact

The damaging effect of landslides on the exposed elements, in particular buildings and infrastructures, can be assessed by multiplying their value by the respective vulnerability coefficients, which depend on the type of phenomena and of their intensity. When individual persons are exposed, it is not appropriate to give a value to human life, although it is done by insurance companies, and the determination of the impact is based on the number of potential victims (see § 5.3).

However the major impact for a mountain road interrupted by a landslide event is generally induced by the economic losses which depend on the hindered industrial, commercial and touristic activities. The determination of this value requires a detailed knowledge of the concerned economic activities, of the possible alternative routes, as well as an appropriate assessment of the potential duration of the road closure.

5.3. Assessment of potential impact related to transit traffic

The fact that the main use of the road is due to vehicles transiting at a given speed implies that there is a certain probability that a vehicle might be hit by a sudden hazard. The methodology used, developed by the Swiss Federal Office for the Environment, Forest and Landscape [BUWAL, 1999], is applicable to rockfall and avalanches.

The number of potentially impacted vehicles N_f is given by:

$$N_f = DTV \cdot g/(v \cdot f) \quad (1)$$

where DTV is the daily average traffic density on the road (two directions), v the average velocity of the vehicle, g the length of stretch of road impacted by the natural hazard, and f the time factor, which is here 24 h times a correction factor function of the distribution of the vehicles.

The number of affected persons S is given by:

$$S = N_f \cdot \beta \cdot \lambda \quad (2)$$

where β is the average number of passengers in a car (assessed here to be equal to 3) and λ is the lethal rate, depending on the type of vehicle and type of event, with:

$\lambda = 0.1$ is a low value (bus, debris flows)

$\lambda = 0.3$ is a medium value (car, avalanche)

$\lambda = 0.5$ is a high value (motorcycle, rockfall)

These formulas allow the computation of the potential victims for each stretch of road.

6. Risk analysis

6.1. Generalities

The information gathered will help building the risk scenarios, considering the hazards due to the various phenomena and the vulnerability factors corresponding to each exposed object, but also the aversion factor (more significant perception of one disaster causing many victims as compared to many accidents causing one victim each) and the impact on the local economy. The risk analysis includes an assessment in terms of human losses, monetary costs due to the potential physical and economic damage and environmental impacts. It is established by multiplying the impacts by the probability of occurrence of each risk scenario, and then by summing the different independent scenarios.

For human life the analysis includes the individual risk, the social risk as well as the potential investment cost to save lives. It is necessary to compare the risk increase due to a certain hazard to the ordinary level of risk induced by current life and to tolerate an extremely low probability of impact if the risk that numerous human lives might be lost simultaneously. It is clear in this respect that the concept of risk may vary from state to state, considering sociological aspects.

It has to be kept in mind that in risk analysis the input parameters do not have fixed values, but are assessed with a certain interval of confidence; on the other hand the limits between risk classes which need to be introduced cannot be fixed in a rigid way. Finally risk varies with time, considering for instance the progressive increase of traffic or the evolution of a slide. Therefore it is appropriate to fix qualitative risk classes based on semi-quantitative elements of information.

In the considered case study the risks are divided into five classes: each of them is represented by a different colour as explained in Table II, based on the federal recommendations (see example of map in Fig. 11).

In order to establish the risk map concerning the studied road, the proposed method includes 5 steps:

- To consider each 250 m long stretch of route.
- To analyse each stretch that is affected by one or several hazards of a given level.
- To assess the vulnerability of each stretch, considering the relevant hazard level.
- To foresee and quantify the possible effects of each hazard.
- To select a risk class for each stretch accordingly.

6.2. *Analysis of specific scenarios*

For each part of the road specifically threatened by a high hazard, an analysis of all potential scenarios has been carried out considering the possible combination of phenomena and the different events that may occur at this spot. For example, the stretch of road corresponding to the crossing of La Frasse Landslide (km 8.250-9.250) is analysed here.

6.2.1. *Hazard level*

This permanently active slide has caused damage to the road very few years after its construction between 1830 and 1835. Since then several studies have been carried out and some stabilizing works have been tempted [DUTI, 1986]. The zone crossed by the road is subject to occasional serious accelerations in particular in 1916-1919, 1966, 1981-1982, 1994 (up to 1 m/week was measured in 1982) whereas the long-term permanent movement varies between 20 and 60 cm/year at the road level, with a slip surface at a depth of more than 30 m. Presently, due to some recent drainage works by pumping in a line of boreholes upstream of the road and to favourable climatic conditions, the movement has been reduced to some centimeters/year [LALOUI *et al.*, 2004].

The hazard level has to consider not only the nearly stable present situation, but the possibility of new crises. Therefore the hazard level is set at a value of 3 (high hazard). Furthermore, the Grande Eau river at the toe of the slide is experiencing a progressive increase in elevation and might eventu-

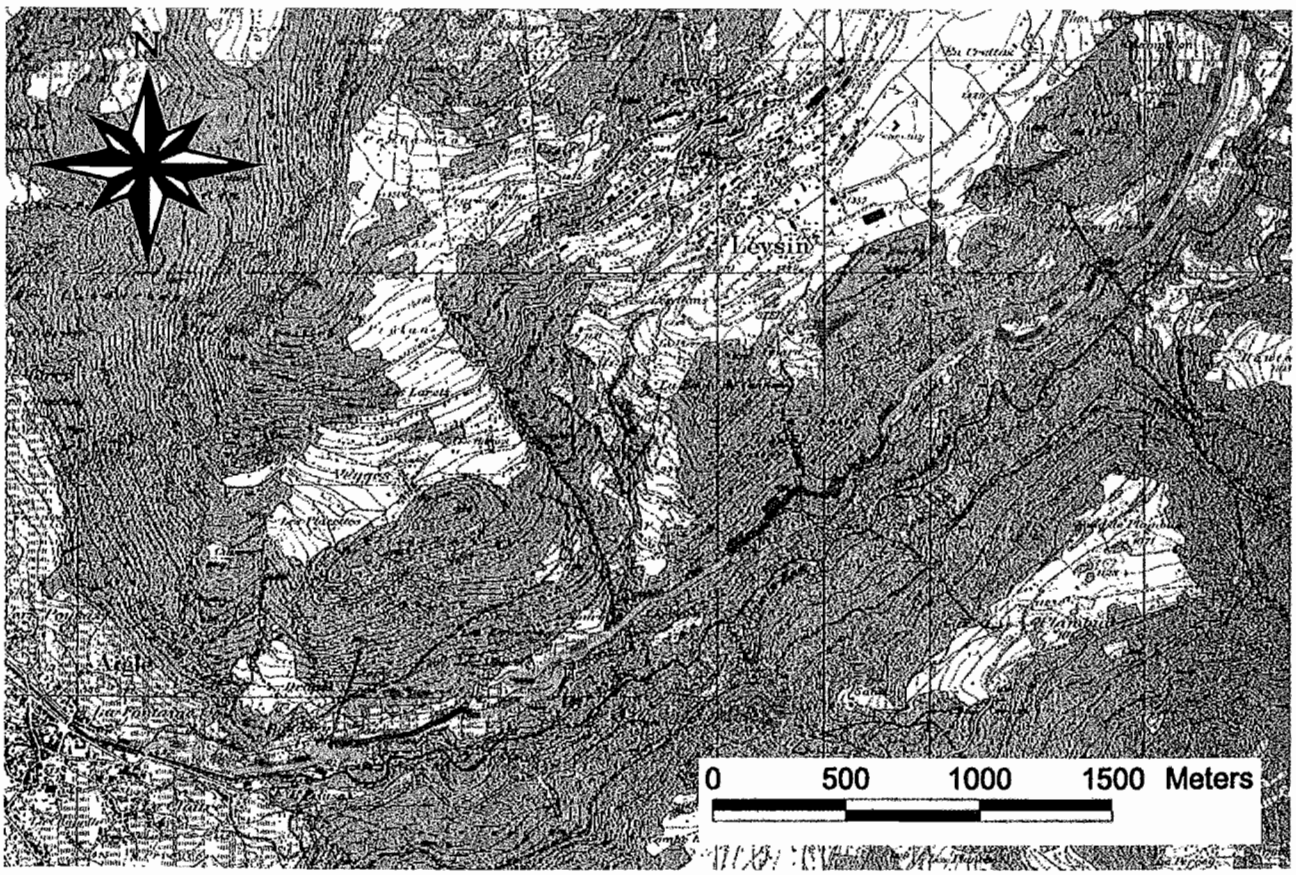


Fig. 11 – Synthetic map expressing the risk level for each 250 m long stretch of the studied road. The risk level varies between 0 (negligible risk - grey colour) and 4 (high risk – red colour) (see Tab. II).
Fig. 11 - Mappa riassuntiva che esprime il livello di rischio per ogni 250 m, lungo l'allungamento della strada studiata. Il livello di rischio varia tra 0 (rischio trascurabile – colore grigio) e 4 (rischio elevato – colore rosso) (cfr. Tab. II).

Tab. II – Description of risk classes.
Tab. II – Descrizione delle categorie di rischio.

Risk level	Colour	Qualification or risk
0	Grey	No assessed risk
1	Yellow	Residual risk: either the risk is very low or the hazard level is high but the zone is protected by specific works that are well designed and maintained
2	Green	Sensibilisation zone: information must be given (sign posts). Special consideration is required for sensitive objects along the road like a gas station
3	Blue	Prescription zone: as people are exposed outside of buildings, namely even in their cars, traffic may be tolerated, but requires control measures (monitoring, maintenance works, study of possible protection works in case of increase of risk level)
4	Red	Prohibition zone: the high risk level requires an immediate realization of protection works and an eventual stop of traffic in case of serious dangers (intense storm for instance), as there is a severe risk for human life

ally be blocked by the sliding mass. Some provisional protection works have been built in the riverbed to limit the erosion phenomena, but more comprehensive stabilizing solutions are presently studied [LALOUI *et al.*, 2004].

6.2.2. *Impact*

As far as vulnerability and impact are concerned, the road transitability is seriously affected by the movements so that the traffic has to be slowed down permanently and sometimes regulated on one line by traffic lights, to allow maintenance works. These normal works, which can be assessed on the basis of the roadway construction costs (approx. CHF 500.–/m or 320 €/m) and of the vulnerability coefficient proposed by Leone [LEONE *et al.*, 1996], of 0.3, represent an annual investment of CHF 100.000.– or 64.000 € per year, if it is considered that two thirds of the whole width on the slide is affected by serious movements. This value is similar to what has been spent by the State on an average during the last years, just for the road.

Along the road there is no building, as most of them are located in a quieter zone, upstream of the fast moving zone crossed by the studied road. The only infrastructures related directly to the road concern the stabilization works (anchored piles, walls, surface drainage channels, drainage boreholes) which represent a total cost of some 2 million CHF (1.3 million €), inducing also an annual cost of some CHF 100.000.– or 64.000 € per year.

The number of vehicles which may be affected by a sudden event (acceleration of the slide), considering their marginal costs, gives a ridiculously low value of CHF 133.– or 85 €. But the drivers and passengers which might be injured following difficult transit conditions leads to a sum varying between 2.600 and 6.600 CHF/person (1660 and 4220 €/person), according to the level of physical damage caused.

6.2.3. *Risk level*

Finally, considering all these aspects in a semi-quantitative scale, it is assessed that the risk level will be equal to 3, namely a medium level, requiring an information action (signposts, monitoring) (see Fig. 5).

The risk level may be quite higher if induced by a rockfall, in particular in a non protected zone, as explained in § 4.2.4, which is qualified as a high risk zone and should require immediate protection works (see red stretch in Fig. 11). Such an event already occurred, but happily without victims. This high risk stretch is unique along the Aigle – L'Etivaz road.

7. Conclusions

The management of natural risks due to several phenomena keeps being a difficult task, but is an increasing necessity in order to plan and carry out the relevant protection works. An application of the proposed methodology is presented here, concerning a major mountain road, which seems to give interesting results. Such an approach allowing a reasonable assessment of the risks in comparative semi-quantitative terms could be used at a regional scale to organize maintenance of protection works of a road network. Presently no European country is applying a rigorous and comprehensive risk analysis method for natural hazard affecting roads, as it has been applied for railway lines in Canada [MACKAY, 1997] or other infrastructures [OBONI & OLDENDORFF, 1997]. It could be therefore useful to test the proposed methodology in different real situations.

Acknowledgements

The authors are grateful to the Office of Roads and Motorways of the Canton of Vaud for the information they supplied on traffic and maintenance work costs.

References

BARDOU E. (2000) – *Data for snow avalanche computation* (personal communication).

BONNARD Ch. (1983) – *Determination of slow landslide activity by multi-disciplinary measurement techniques*. Proc. Int. Symp. on Field Measurements in Geomechanics, Zurich, 1, pp. 619-638.

BONNARD Ch. (2004) – *Assessment and prediction of landslide movements: criteria for hazard management*. Proc. 9th Int. Symp. on Landslides, Rio de Janeiro (opening lecture to be published).

BONNARD Ch., NOVERRAZ F., PARRIAUX A. (1987) – *Origin of groundwater likely to affect a large landslide*. Proc. IXth Env. Conf. on Soil Mech. and Found. Engrg., Dublin, 1, pp. 389-392.

BOSSY F. (1999) – *Le glissement de la Lécherette*. Travail de diplôme, CHYN, Neuchâtel, 80 pp.

BUWAL (1999) – *Risikoanalyse bei gravitativen Naturgefahren. Methode*. Bundesamt für Umwelt, Wald und Landschaft, Bern, 115 p.

DUTI (1986) – *Le Glissement de La Frasse*. Projet d'Ecole, Détection et Utilisation des Terrains Instables, Ecole Polytechnique Fédérale de Lausanne, 229 pp. + annexes.

LALOUI L., TACHER L., MORENI M., BONNARD Ch. (2004) – *Hydro-mechanical modeling of crises of large landslides: application to the La Frasse Landslide*. Proc. 9th Int. Symp. on Landslides, Rio de Janeiro (to be published).

LEONE F., ASTE J.-P. LEROI E. (1996) – *Vulnerability assessment of elements exposed to mass movements: working toward a better risk perception*. Proc. 7th Int. Symp. on Landslides, Trondheim, 1, pp. 263-268.

MACKAY C.H. (1997) – *Management of rock slopes on the Canadian Pacific railway*. Proc. Int. Workshop on Landslide risk assessment, Honolulu. D. Cruden & R. Fell, (Eds.), pp. 271-275.

NOVERRAZ F. (1994) – *Cartes d'instabilité de terrain du Canton de Vaud. Rapport conclusif et explicatif des travaux de levé de cartes*. Rapport pour le service de l'aménagement du territoire du Canton de Vaud. EPFL-LMS, 54 pp.

NOVERRAZ F., BONNARD Ch., BURDET L. (1993) – *Cartes d'instabilité du Canton de Vaud dans le cadre du plan directeur cantonal*. C.R. Conf. Int. sur la prévention des catastrophes naturelles, Lausanne. Doc. SIA D 0110, pp. 111-121.

NOVERRAZ F., BONNARD Ch., DUPRAZ H., HUGUENIN L. (1998) – *Grands glissements de versants et climat*. Rapport final d'un projet de recherche PNR31, FNRS, Berne. v/d/f Verlag, 314 pp.

OBONI F. & OLDENDORFF G. (1997) – *Integrating risk and crises management: Meeting the needs of a sophisticated society*. Proc. Int. Workshop on Landslide risk assessment, Honolulu. Eds. D. Cruden & R. Fell, pp. 317-326.

OFAT; OFEE; OFEFP (1997) – *Prise en compte des dangers dus aux mouvements de terrain dans le cadre des activités de l'aménagement du territoire*. Office fédéral de l'aménagement du territoire, Office fédéral de l'économie des eaux, Office fédéral de l'environnement, des forêts et du paysage. OCFIM, Berne, 32 p.

TURNER A.K., SCHUSTER R.L. (Eds.) (1996) – *Landslides, investigation and mitigation*. Special Report 247, Transportation Research Board, National Research Council, Washington, USA.

VARNES D.J. (1984) – *Landslide hazard zonation: a review of principles and practice*. UNESCO, Paris, 63 pp.

Valutazione della vulnerabilità e del rischio per una strada di montagna che incrocia frane

Sommario

Le catastrofi naturali sono in costante aumento principalmente per la maggiore esposizione dei beni materiali e della popolazione nei riguardi di un gran numero di pericoli naturali, oltre che per i possibili effetti secondari indotti localmente dal riscaldamento globale.

Dopo una breve introduzione sulla rilevanza delle catastrofi naturali nel mondo e sulla questione della gestione globale dei rischi, l'articolo si concentra su un caso di studio.

Nelle Svizzera occidentale, una importante strada di montagna, della lunghezza complessiva di 25 km, collega la città di Aigle con il paese di L'Etivaz, attraverso il passo del Col des Mosses (q. 1445 m s.l.m.). La strada in questione è minacciata da molteplici pericoli naturali quali: caduta massi, colate di fango, valanghe, oltre che da due frane rispettivamente nominate La Frasse e La Lécherette che hanno originato numerose crisi nel passato.

Al fine di adottare misure di prevenzione in grado di evitare la trasformazione dei pericoli naturali in catastrofi, si è proceduto a realizzare un inventario completo dei rischi che minacciano la strada.

L'analisi del rischio è stata effettuata in più fasi. La prima fase ha riguardato l'approfondimento delle conoscenze sui fenomeni naturali – vale a dire posizione, aspetti geologici e morfologici, stato di attività, dati storici sugli eventi – finalizzato alla redazione della carta-inventario dei fenomeni. La seconda fase si è concretizzata nella redazione della carta della pericolosità nella quale sono individuati tre gradi di pericolosità (bassa, media e alta). La terza fase ha riguardato lo studio della vulnerabilità della zona; la quarta, infine, la definizione del rischio, che è stato assunto variabile da 0 min a 4 mass, lungo tratti di strada della lunghezza di 250 m ciascuno.