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ROCK FALL HAZARD ASSESSMENT: FROM QUALITATIVE TO QUANTITATIVE FAILURE PROBABILITY

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ABSTRACT: A new method (HGP) is proposed to estimate the failure probability of potentially unstable rock masses in a homogenous area, as a function of time. It is based on both geomechanical and historical approaches: the first one is aimed to classify the rock masses according to their relative failure probability, but the time factor can not be approached by a mechanical analysis; the second one to estimate the mean expected rock fall number in the studied area, for the considered period and for different volume classes. This rock fall frequency can be estimated from a rock fall inventory, directly or indirectly using a power law for the volume distribution. A relation between these frequencies and the erosion rate is established, which allows to approach the former from a paleogeographical study. The failure probabilities can be calculated from the expected total rock fall number in the area, and the numbers of potential rock falls with different relative probabilities. The method is applied to the case of the Grenoble area. Development of rock fall data basis is needed to improve both geomechanical and historical approaches.

Keywords: rock fall, hazard assessment, failure probability.

1 INTRODUCTION

Rock fall hazard results from two processes: detachment of a rock volume from the upper part of the slope (local failure of the slope), and propagation of this volume along the slope. A deterministic evaluation of rock fall hazard in an extended area would consist in determination of potentially unstable rock volumes, their departure times and their trajectories. Unfortunately, the knowledge of rock slope structure and of failure and propagation processes is not sufficient to make possible such a deterministic evaluation.

Mechanical methods exist to calculate the trajectory of a rock fall or avalanche for a given unstable rock volume (e.g. Hungr, Evans 1996; Fell et al. 2000; Guzzetti, Crosta 2001; Labiouse et al. 2001). For individual blocks, the probability to reach a given point with a given energy can be calculated. But it is a conditional probability because it is assumed that the potentially unstable block has gone out from the slope. We will call it the "propagation probability". To get the real "reach probability" of a point, it must be multiplied by the probability of detachment (or "failure probability"), which obviously depends on the considered period (usually of the order of one century for land use studies).

Probabilistic methods exist to analyse the future stability of designed slopes (Hoek 1998a; Nilsen 2000). Most of them use Monte-Carlo simulation to obtain the probability for the safety factor to be greater than 1. But they are not adapted to natural slopes for which one knows that their safety factor is greater than 1 under the present conditions and the question arises of their future evolution. At the present time, no method exists which gives the failure probability of a potentially unstable rock volume as a function of the considered period. The existing methods to evaluate rock fall hazard in natural slopes give a qualitative and relative evaluation of the failure probability (Cancelli, Crosta 1993; Hoek 1998b; Rouillet et al. 1998; Mazzoccola, Sciesa 2000; Mazzoccola, Sciesa 2001; Mazzoccola 2001).

The purpose of this paper is to present a new approach to estimate an absolute quantitative probability of failure for potentially unstable rock masses. This approach, called HGP (Historical, Geomechanical, Probabilistic), combines the results of geomechanical and historical analyses to estimate the failure probability (Dussauge et al. 2001; Vengeon et al. 2001; Hantz et al. 2002). Knowing the failure probability of a given rock volume in the slope and the propagation probability to any point downhill, the real reach probability of any point could be calculated and compared with the probabilities of other natural hazards like earthquakes or floods. This comparison may be useful for land use policy.

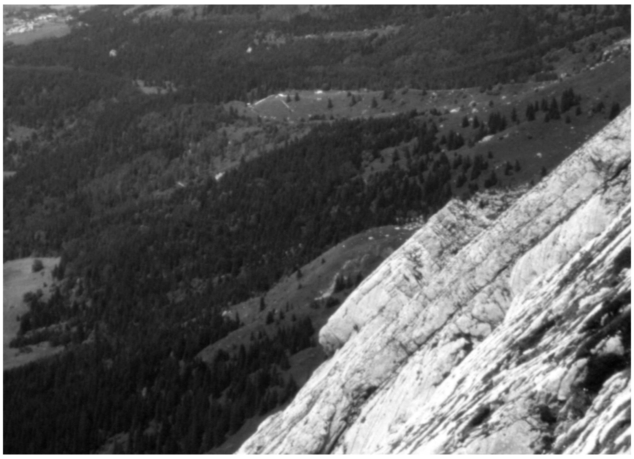

Figure 1. A potentially unstable rock mass of about 10,000 m^3. The slab is 6 m thick. The potential failure mechanism is a plane slide.

2 GEOMECHANICAL ANALYSIS

Based on the factors which influence the mechanical stability of a rock mass, the mechanical analysis is aimed to detect potentially unstable rock masses (or potential instabilities) and to classify them according to their failure probability in a given estimation period.

2.1 *Detection of potential rock fall sources*

The detection is based on the identification of failure configurations, and on the search for indications of recent or present movements (the term "recent" must be regarded in a geological sense and refers to an age up to one century). The objective is to localise and to define, as precisely as possible, potentially unstable rock masses, which then will be individually evaluated. Each rock mass, called "localised potential instability", must be characterised by its total volume and the dimensions of the individual blocks it consists in. An example of localised potential instability is given on the Figure 1.

According to the nature of the slope or the investigation method, it may be impossible to identify localised instabilities, but only to detect the possibility that potentially unstable rock masses exist in a given area of the slope under study. These "diffuse potential instabilities" can be detected by comparing the geological structure of the rock mass and the topography of the slope. The principle of the detection was given by Hoek, Bray (1981) for a slope defined by an inclined plane and a horizontal upper surface, and by Goodman, Shi (1985) for the general case of a slope defined by several planes. The detection may be automated by using Geographical Information Systems (e.g. Tanays et al. 1989, 1992; Jaboyedoff et al. 1999).

2.2 *Factors influencing failure probability of a potentially unstable rock mass*

If recent movements are proved, the probability of detachment of the slowly moving rock mass is usually considered as high. According to the velocity, an evaluation for the short term, and not only for mapping, may be necessary. It must be based on monitoring of the slope. The methodology for interpretation of monitoring data is out of the scope of this paper (see Rochet 1992; Azimi, Desvarreux 1996; Hantz 2001). Without monitoring, opening of tension cracks is an indication of movement. Increasing of block fall frequency may indicate the slow movement of a larger rock mass.

The evaluation of the failure probability of presently stable rock masses is more difficult (why would they become unstable and when?). The failure may be due to a decrease of the rock mass strength, an increase of the active stresses or both of these phenomena. These variations can be induced by human activities, which are normally predictable, or by natural processes. These latter may be continuous and progressive (and theoretically detectable) or discontinuous and uncertain. Of course, the present state of stability also influences the failure probability for a future period: the higher the present stability, the lower the failure probability. The factors that have to be considered in the evaluation of the failure probability of a presently stable rock mass may be classified in four categories: present state of stability; continuous natural processes; discontinuous and uncertain natural processes; human modifications of the slope.

Theoretically, the present state of stability can be analysed with a classical stability analysis and quantified by means of a safety factor. Despite the important uncertainty that affects the involved parameters, stability analyses are largely used for rock slope design, in a deterministic or probabilistic way. In the deterministic approach, the uncertainty is coped with by requiring a value greater than 1 for the safety factor (1.5 for example) and accordingly modifying the slope. In the probabilistic approach, the slope is designed in order to reach an accepted failure probability. On the contrary, in rock slope evaluation, the slope has to be considered in its actual state and the uncertainty remains. Moreover, the knowledge of the present safety factor of a slope (or its probability distribution in the probabilistic approach) is not sufficient to evaluate the failure probability as a function of time.

Continuous natural processes that can decrease the stability are weathering and dissolution, damage due to repeated subcritical stresses, permafrost retreat, erosion, accumulation of material, tectonic deformations. These processes act at a geological time scale and with very low rates, which make them difficult to observe and quantify.

Discontinuous natural processes susceptible to produce failure are earthquakes, water pressure or water content increase, rapid erosion or accumulation. They are induced by external exceptional events such as heavy rainfall, rapid thaw, earthquake or debris flow. Seismologists or climatologists can give the occurrence probability of some of these events, but their influence on the slope is difficult to quantify. For earthquakes, dynamic stability analyses are uncertain for the same reasons than static ones. For ground water, its flow pattern in rock masses is poorly known and quantitative analysis is highly uncertain.
Human modifications of the slope may be produced by excavations, blasting vibrations, modifications of surface or underground water flow. They are normally known and predictable, and can be input in static or dynamic stability analyses.

2.3 *Qualitative evaluation of the failure probability*

Most of the existing methods for failure probability evaluation use the above-mentioned influencing factors to grade the potentially unstable rock masses. Some of them are directly based on the expert experience and judgement, and give a qualitative classification (e.g. Effendiantz 2001). For example, it may consist in three classes corresponding to high, medium and low failure probabilities. Other ones use a weighting of the influencing factors to calculate a hazard index (e.g. Baillifard et al. 2001; Mazzoccola, Sciesa 2000, 2001; Mazzoccola 2001). But the attribution of weighted values is based again on the experts experience and judgement.

2.4 *Relative failure probabilities*

At the present time, no method gives a true quantitative failure probability for a given potentially unstable rock mass. But one can expect that statistical analysis, similar to the ones which have developed for landslides hazard assessment (Aleotti, Chowdhury 1999; Carrara et al. 1990), will develop in the near future for rock falls. These analysis should give more objective results than the existing empirical approaches.

The new approach proposed in this paper (HGP approach) supposes that the order of magnitude of the ratio r between the probabilities associated to the different probability classes is known. In other words, it supposes that relative failure probabilities can be estimated. If the unknown mean probability corresponding to the higher probability class is p_1, the mean probability corresponding to the second class is $p_2 = p_1 / r$.

Note that the expected mean number of rock falls in the studied area, μ, for the estimation period (of length T) and the considered volume class, is

$$\mu (T) = \Sigma n_i \, p_i \tag{1}$$

where n_i is the number of potential rock falls in the class i. It can be expressed as a function of r and the unknown probability p_1.

At the present day, the influence of time can not be quantified from geomechanical analysis, but it can be approached from a global historical or morphodynamical analysis of the homogenous area which contains the potentially unstable rock masses.

3 HISTORICAL ANALYSIS

The objective of the historical analysis is to estimate the mean number of rock falls, μ, for the estimation period and the considered volume class. It may be estimated directly from an exhaus-

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tive inventory of rock falls in the studied area, for the considered volume class, or indirectly, using statistical models of rock slope erosion. Estimation methods will be presented below, illustrated with the example of the Grenoble area. The Grenoble area is surrounded with about 120 km of cliffs, whose height varies between 50 and 450 m (Fig. 2). They consist mainly in Thitonian, Valanginian and Urgonian limestone strata that are usually slightly inclined inside the slope. They are relatively rectilinear on several km (sometimes almost 20 km), which indicates a uniform retreat rate. Consequently, the studied area can be considered relatively homogenous from a geological and morphodynamical point of view.

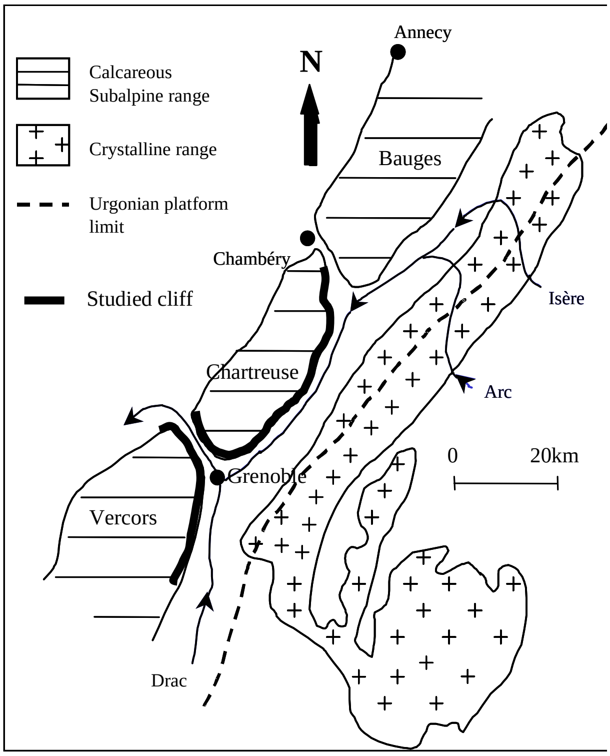

Figure 2. Simplified geological map of Grenoble area.

3.1 *Rock fall inventory*

Inventories may be available from road, railway or forest services, or from natural parks. The observation period may be as long as one century. The larger the considered volumes are, the longer the observation period or the broader the area must be. For small rock falls on a road, significant values may be drawn from some years of observation. For example, 423 rock falls have been observed during a 4 years period, on a 11 km road section, in La Réunion island (CFGI 2000); on the other hand, 33 rock falls between 100 and 1000 m^3 have been reported in 65 years, along 120 km of cliff in the Grenoble area (see later).

A rock fall inventory for the Grenoble area has been made by a forest service (RTM, which means mountain land rehabilitation), which have recorded rock falls occurring in the 20th century and some others occurred before, which have left physical or historical traces (RTM 1996). It comprises about one hundred rock falls having occurred in the four last centuries. The exhaustivity of the inventory depends of the volume class. The bigger rock falls have left traces, which remains visible for several centuries. So the inventory has been assumed to be exhaustive for the 4 last centuries for the volume class 1 to 10 hm^3, and for the 2 last centuries for the volume class 0.1 to 1 hm^3. Considering the last century, rock falls in the class 10 m^3 - 100 m^3 are less numerous than in the class 100 m^3 - 1000 m^3. It proves that the inventory is not exhaustive under 100 m^3. We assumed that it is roughly exhaustive for the period 1935-2000 and the volumes between 100 m^3 and 100 000 m^3. The numbers of rock falls for the different volume classes and considered periods are given in the Table 1, with the corresponding "observed" class frequencies and cumulated frequencies.

Table 1. Observation period, number of observed rock falls, observed class frequency and cumulated frequency (per century), calculated cumulated frequency and class frequency (assuming a power law distribution) for each volume class (calcareous cliffs in the Grenoble area).

Volume class (m^3)	10^2-10^3	10^3-10^4	10^4-10^5	10^5-10^6	10^6-10^7
Observation period	1935-2000	1935-2000	1935-2000	1800-2000	1600-2000
Rock fall number	33	9	6	3	2
Observed frequency (per century)	51	14	9	1.5	0.5
Observed cumulated frequency (per century)	76	25	11	2.0	0.5
Calculated cumulated frequency (per century)	91	26	7	2.1	0.6
Calculated frequency (per century)	65	18	5	1.5	0.6

3.2 *Volume distribution of rock falls*

The volume distribution of the rock falls have been studied by some authors (e.g. Wieczorek et al. 1992; Hungr et al. 1999; Dussauge-Peisser et al. 2002). For the inventories which have been analysed, the cumulated distribution of rock fall volumes follows a power law in a volume range covering at least 4 orders of magnitude:

$$f(V) = a V^{b} \tag{2}$$

where $f(V)$ is the frequency of rock falls with a volume greater than V, and a and b are constants. According to the inventory, b varies between 0.4 and 0.7. a is the frequency of rock falls with a volume greater than 1 m^3, supposing that the power law is valid down to this value. It depends on the cliff area concerned by the inventory and on the activity of the processes causing the failure of rock masses. To compare different areas, we define the specific rock fall frequency, as the number of rock falls with a volume greater than 1 m^3, per century and per unit cliff area (hm^2). This specific frequency varies of at least 2 orders of magnitude according to the geological and morphodynamical contexts (Dussauge-Peisser et al. 2002).

An observed frequency (Table 1) must be regarded as an estimate of the mean value of a random variable. Considering that the rock falls are rare, independent and discrete events, the Poisson law applies to describe this variable, as for the frequency of earthquakes. Supposing that the power law reflects physical processes, fitting the observed frequencies to a power law must give better estimates of the mean frequencies. For the Grenoble area, fitted (calculated) frequencies are given in the Table 1. Moreover, if the law was valid outside the observed volume range, extrapolations would be possible.

3.3. *Rock fall erosion rate*

With the assumption that the power distribution law is valid for the whole range of possible volumes, the eroded volume per century, due to rock falls of a volume comprised between V_1 and V_2 is:

$$V_t = \int_{n(V_2)}^{n(V_1)} V dn = \frac{ab}{(1-b)} (V_2^{1-b} - V_1^{1-b}) \tag{3}$$

b being lower than 1, this integral does not converge when V_2 tends towards infinity. But V_2 is limited by a maximal possible volume V_{max}, depending notably on the slope dimensions. Then the true rock falls distribution law is truncated.

For $V < V_{max}$: $n(V) = a\,V^{-b}$

For $V > V_{max}$: $n(V) = 0$ (4)

The total eroded volume per century, due to rock falls, is then:

$$V_t = \int_0^\infty V dn = \frac{a}{(1-b)} V_{\max}^{1-b} \quad (5)$$

If S is the total area of the slope covered by the inventory, the erosion rate is:

$E = V_t / S$ (6)

If b was known, it would be possible to evaluate the parameter a from the erosion rate. The later can be estimated from paleogeographical studies (time scale of several million years) or historical measurements (time scale of several years).

For the cliffs around Grenoble, the maximal possible rock fall volume is estimated to 10^7 m^3. The Table 2 gives the eroded volume per century for each volume class, the total eroded volume and the erosion rate.

Table 2. Fallen volumes per century (calculated from the power law distribution) and erosion rate for calcareous cliffs in the Grenoble area.

Volume class (m^3)	< 10^2	10^2-10^3	10^3-10^4	10^4-10^5	10^5-10^6	10^6-10^7
Fallen volume per century (m^3)	10,893	19,807	55,825	157,336	443,433	2834,632
Total fallen volume per century	3521,927 m^3					
Cliff area	24.10^6 m^2					
Erosion rate	0.15 m/century					

Acording to Arnaud (1979) and Gidon (1996), the eastern limit of the Urgonian platform when sedimentation occurred was 10 to 15 km from the actual cliff (Fig. 2), and it began to be eroded about 10^7 years ago. From this paleogeographical approach, the order of magnitude of the erosion rate is 0.1 m/century. The rates obtained from the rock fall inventory (for 10^2 years) and from the paleogeographical approach (for 10^7 years) are of the same order of magnitude. If b is site independent, it means that the order of magnitude of the rock fall frequencies can be estimated from the erosion rate, without inventory.

4 QUANTITATIVE EVALUATION FOR FAILURE PROBABILITY

Considering the equation (1), the historical analysis yields the expected number of rock falls, μ, for a given period and a given volume class, and the geomechanical analysis yields the numbers n_i of potential rock falls, for each probability class, and the relative probability r between these classes. The unknown probability p_1 can then be calculated. The method will be illustrated with the case of the Grenoble area, for the volume class 10^5-10^6 m^3, in which a mean number of 1.5 rock falls is expected each century (Table 1). The geomechanical analysis being not completed, suppose that 30 potentially unstable rock masses have been detected and classified in 2 classes, the probability associated to the second class being 10 or 5 times lower than to the first one. Different distributions of the instabilities between the two classes have been considered. The obtained failure probabilities in the next 100 years are given in the Table 3. For example, with 10 potential instabilities in the first class, 20 in the second one and a relative probability between them of 10, the "individual" failure probability is 0.125 for the rock masses belonging to the first class, and 0.0125 for the ones in the second class. Depending on the r value and the way the experts distribute the instabilities, the failure probability for the most probable ones (first class) varies from 0.05 to 0.4. These results give the order of magnitude of this probability. It means that the failure of an instability belonging to the first class can be considered as a 1000-year return period event rather than a 100-year return period one.

Table 3. Failure probabilities, in the next 100 years, for 30 potential instabilities distributed in two classes, assuming that 1.5 rock falls are expected in the whole area. Two different relative probabilities (failure probability in the class 1 / failure probability in the class 2) and different distributions between the two classes have been considered

Relative probability class1/class2 (r)	Number of instabilities in class 1 (n_1)	Number of instabilities in class 2 (n_2)	Failure probability for class 1 (p_1)	Failure probability for class 1 (p_2)
10	1	29	0.385	0.038
10	5	25	0.200	0.020
10	10	20	0.125	0.013
10	15	15	0.091	0.009
10	20	10	0.071	0.007
10	25	5	0.059	0.006
10	29	1	0.052	0.005
5	1	29	0.221	0.044
5	5	25	0.150	0.030
5	10	20	0.107	0.021
5	15	15	0.083	0.017
5	20	10	0.068	0.014
5	25	5	0.058	0.012
5	29	1	0.051	0.010

5 CONCLUSION

The HGP method yields an order of magnitude of the failure probability for potentially unstable rock masses, which have been classified according to geomechanical criteria. This gives a more quantitative significance to the qualitative evaluations which are usually affected to the potential instabilities (e.g. "high, medium or low probability"). By this way, rock fall hazard can be compared with other natural hazards, such as floods or earthquakes, for which 100-year or 1000-year return period events can be determined. The method can be used for relatively homogenous area, where a historical rock fall inventory is available or can be realised. A relation between rock fall frequencies and the erosion rate has been established, which suggests that the formers could also be obtained from the erosion rate of the area. A better knowledge of the rock fall volume distribution, by means of data basis, is needed to validate this approach.

Presently, the weak side of the HGP method is that the relative probabilities result from a subjective evaluation. But improvements are expected from statistical analysis of detailed rock fall data basis, which are planned in several Alpine countries.

REFERENCES

Aleotti, P., Chowdhury, R. 1999. Landslide hazard assessment: summary review and new perspectives. *Bull Eng Geol Env*, 58: 21-44.

Azimi, C., Desvarreux, P. 1996. Quelques aspects de la prévision des mouvements des terrain. *Revue française de géotechnique*, 76: 63-75.

Baillifard, F., Jaboyedoff, M., Rouiller, J. D., Tosoni, D. 2001. Matterock, Prévention des mouvements de versants et des instabilités de falaises. *Programme Interreg II C*: 70-84.

Cancelli, A., Crosta, G. 1993. Hazard and risk assessment in rockfall prone areas. *Proc Conf on Risk and Reliability in Ground Engineering, London*: 177-190.

Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V., Reichenbach, P. 1991. GIS techniques and statistical models in evaluating landslide hazard. *Earth Surface Processes and Landforms*, 16: 427-445.

CFGI (Comité Français de Géologie de l'Ingénieur) 2000. *Caractérisation et cartographie de l'aléa dû aux mouvements de terrain*. Collection "Environnement - Les risques naturels", Laboratoire Central des Ponts et Chaussées, Paris.

Cruden, D.M., Varnes, D.J. 1996. Landslide types and processes. *Landslides, Investigation and Mitigation*: 36-75. National Academy Press, Washington, D.C.

Dussauge, C., Giraud, A., Grasso, J.R., Hantz, D., Vengeon, J.M. 2001. Historical and geological approach to rock fall hazard assessment. *European Geophysical Society, XXVI° General Assembly, Nice, Geophysical Research Abstract*, 3, GRA 8625.

Dussauge-Peisser, C., Helmstetter, A., Grasso, J.R., Hantz, D., Desvarreux, P., Jeannin, M., Giraud, A. 2002. Probabilistic approach to rock fall hazard assessment: potential of historical data analysis. *Natural Hazards and Earth System Sciences*, 2: 1-13.

Effendiantz, L. 2001. La méthodologie LPC, *Prévention des mouvements de versants et des instabilités de falaises, Programme Interreg II C*: 108-114.

Fell, R., Hungr, O., Leroueil, S., Riemer, W. 2000. Keynote lecture - geotechnical engineering of the stability of the natural slopes and cuts and fills in soil. *Proc. GeoEng2000, Melbourne, Australia*, 1.

Goodman, R. E., Shi, G. H. 1985. *Block theory and its application to rock engineering*. Prentice-Hall.

Guzzetti, F., Crosta, G. 2001. Programma Stone, Prevenzione dei fenomeni di instabilità delle pareti rocciose. *Programme Interreg II C*: 206-211.

Hantz, D. 2001. Ingénierie des pentes rocheuses naturelles et artificielles. *Les Techniques de l'Industrie Minérale*, 10, 66-75.

Hantz, D., Dussauge-Peisser, C., Jeannin, M., Vengeon, J.M. 2002. Danger d'éboulements rocheux : de l'opinion d'expert à une évaluation quantitative. *Symp. Geomorphology: from expert opinion to modelling, Strasbourg*: 115-122.

Hoek, E., Bray, J.W. 1981. Rock Slope Engineering. *The Institution of Mining and Metallurgy, London*.

Hoek, E. 1998a. Factor of safety and probability of failure. *Rock Engineering, Course notes*. www.rockeng.utoronto.ca/hoekcorner.htm, 8: 105-114.

Hoek, E. 1998b. Analysis of rockfall hazards. *Rock Engineering, Course notes*. www.rockeng.utoronto.ca/hoekcorner.htm, 9: 115-136, 1998b.

Hungr, O., Evans, S. G. 1996. Rock avalanche runout prediction using a dynamic model. *Procs. 7th Int. Symp. on Landslides, Trondheim, Norway*, 1: 233-238.

Hungr, O., Evans, S.G., Hazzard, J. 1999. Magnitude and frequency of rock falls along the main transportation corridors of southwestern British Columbia. *Canadian Geotechnical Journal*, 36: 224-238.

Jaboyedoff, M., Baillifard, F., Marro, C., Philippossian, F., Rouiller, J. D. 1999. Detection of rock instabilities: Matterock methodology, *Joint Japan-Swiss Sem. on Impact Load by Rock Falls and Protection Structures, Kanazawa, Japan*: 37-43.

Labiouse, V., Heidenreich, B., Desvarreux, P., Viktorovitch, M., Guillemin, P. 2001. Etudes trajectographiques. *Prévention des mouvements de versants et des instabilités de falaises, Programme Interreg II C*: 155-205.

Mazzoccola, D., Sciesa, E. 2000. Implementation and comparison of different methods for rockfall hazard assessment in the Italian Alps. *8th Int. Symp. on Landslides, Cardiff*, 2, 1035-1040. Thomas Telford.

Mazzoccola, D., Sciesa, E. 2001. La metodologia RHAP (Rockfall Hazard Assessment Procedure). *Prevenzione dei fenomeni di instabilità delle pareti rocciose, Programme Interreg II C*: 84-95.

Mazzoccola, D. 2001. La metodologia RES. *Prevenzione dei fenomeni di instabilità delle pareti rocciose, Programme Interreg II C*: 96-108.

Nilsen, B. 2000. New trends in rock slope stability analysis. *Bull Eng Geol Env*, 58, 173-178.

Rochet, L. 1992. Mouvements de versants de grande ampleur: auscultation, diagnostic, surveillance. *Bull Eng Geol Env*, 45: 43-57.

Rouillet, J.D., Jaboyedoff, M., Marro, C., Philippossian, F., Mamin, M. 1998. Matterock: une méthodologie d'auscultation des falaises et de détection des éboulements majeurs potentiels. *Rapport PNR 31*, VDF, Zurich.

RTM 1996. *Inventaire des mouvements rocheux, Secteur de l'Y grenoblois*. Rapport du Service de Restauration des Terrains en Montagne de l'Isère, Grenoble, France.

Tanays, E., Cojean, R., Hantz, D., Savary, R. 1989. Automatisation de la détection des risques de rupture et de l'évaluation de la stabilité des flancs d'une mine à ciel ouvert. *Industrie minérale, les techniques*, 3-89: 35-45.

Tanays, E., Cojean, R., Hantz, D. 1992. A software to design open pit geometry and to draw open pit plans. *Int. Journal of Surface Mining and Reclamation*, 6: 91-98.

UNESCO (the International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory) 1990. A suggested method for reporting a landslide. *Bull Eng Geol*, 41: 5-12.

Vengeon, J.M., Hantz, D., Dussauge, C. 2001. Prédictibilité des éboulements rocheux : approche probabiliste par combinaison d'études historiques et géomécaniques. *Revue Française de Géotechnique*, 95/96: 143-154.

Wieczorek, G.F., J.B. Snyder, C.S. Alger, Isaacson, K.A. 1992. Yosemite historical rockfall inventory. *U.S. Geol.Surv. Open File Report*, 92-387, 38.