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Quantitative assessment of diffuse rock fall hazard along a cliff foot

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Abstract. Many works have shown that the relation between rock fall frequency and volume is well fitted by a power law. Based on this relation, a new method is presented which allows estimating the fall frequency and probability for a wall section in a homogenous cliff, considering all possible rock fall volumes. The hazard for an element located at the foot of the cliff, with a minimal energy, is also estimated. The method has been applied to an itinerary, for which the human risk has also been estimated. Rock fall inventories featuring the location, date, and volume of the falls and the dimensions of the fallen compartments (width, length, and thickness) are needed for better estimating of hazard and risk.

1 Introduction and terminology

In this paper, the term "rock fall" is used in its usual sense, given for example by Cruden et al. (1996). A rock fall can result from a subsequent rock slide or rock topple. For the terms related to hazard and risk assessment, we use the definitions recommended by the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Technical Committee on Risk Assessment (Fell et al., 2005). Before it occurs, a rock fall can be qualified as a potential danger. The hazard is the probability (between 0 and 1) that it occurs within a given period of time, which may be estimated in an objective or subjective way. The hazard can also be the probability of the magnitude of a given quantity (kinetic energy for example) to be reached. For land-use planning, the period of time which is considered is usually one century (MATE and METL, 1999). The risk is a measure of the probability and the severity of an adverse effect to life, health, property, or the environment. It can be expressed as the probability of an adverse event times the consequences if the event occurs. The elements at risk may be population, buildings, infrastructure, environmental features, or economic activities.

The rock fall danger which is considered in this paper is the fact that a given element at risk is reached by a rock mass (consisting of one or several blocks). It results from two events: (a) the detachment of a rock mass from the rock wall due to a failure process; (b) the propagation of this rock mass down to the element at risk.

The rock fall hazard may be defined as the probability of a rock fall of a given magnitude (or kinetic energy) reaching the element at risk, which can be expressed as the probability of detachment (or failure probability) times the probability of the rock mass reaching the element given that it detaches from the rock wall (propagation probability).

The probability of detachment may concern a particular, well defined rock mass (located danger) or a part of the rock wall, from which a rock mass can detach anywhere (diffuse danger). In this paper, only the second case will be considered.

In the present state of knowledge, a quantitative rock fall hazard assessment is only possible when a historical inventory is available for the area considered (Vengeon et al., 2001; Hantz et al., 2003a, b). Without such an inventory, a qualitative assessment is achieved, mainly based on expert judgment (Groupe Falaise, 2001; Hantz et al., 2003b; Effendiantz et al., 2004). Examples of quantitative rock fall hazard and risk assessment are given by Hungr et al. (1999), Fell et al. (2005), Picarelli et al. (2005), Corominas et al. (2005), Jaboyedoff et al. (2005), Agliardi et al. (2009), and Abbruzzese et al. (2009). In these examples, a given volume range of rock falls is considered. This paper presents a method to calculate rockfall hazard and risk using a normalized frequency and taking into account all the possible rock fall volumes, from the smallest to the largest possible ones, using a power law relation between the volume and the frequency of the rock falls.

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2 Rock fall (failure) frequency

Considering a geological time scale, rock falls are repetitive events and represent one of the main erosion processes. At a human time scale and a particular rock wall spatial scale, only the smallest ones are sufficiently frequent for their frequency to be determined from an inventory. Indeed, the size of the spatial-temporal observation window is usually too small for the frequency of larger rock falls to be determined. But in some cases, the shortness of the observation period can be compensated by the extent of the observation area, should the area be sufficiently homogenous. This is the case for some calcareous cliffs, the structure and morphology of which are relatively constant on several kilometers or tens of kilometers. For example, the calcareous cliffs which constitute the west side of the large valley called "Sillon Subalpin" near Grenoble have a rectilinear shape, which indicates a uniform rate of retreat and therefore a relatively homogenous behavior in terms of rock falls.

Many works have shown that the relation between rock fall frequency and volume is well fitted by a power law (for example, Dussauge-Peisser et al., 2002; general review by Picarelli et al., 2005). For a given rock wall, the number of rock falls per unit of time (frequency = F) with volume greater than V (in m^3) is given by:

$$F = \alpha V^{-b} \tag{1}$$

where α = number of rock falls, per unit of time, with volume greater than $1\,m^3$; and b = another constant. The constant α depends on the size of the considered area and of the geological and geomorphological conditions. Concerning the constant b, a review by Dussauge-Peisser et al. (2002) and recent work by Dewez et al. (2009) have shown b values ranging between 0.4 and 0.7.

For the Grenoble calcarous cliffs (French Alps), the rock fall frequency has been estimated from an inventory carried out by a forest service (RTM 38) and completed by the Grenoble University. This inventory concerns rock falls of volume between 10^2 and $10^7\,m^3$, distributed on a wall area of 200 m in average height and 120 km in length. The observation period considered was 65 yr for the volumes smaller than $10^5\,m^3$, and several centuries for larger volumes (Hantz et al., 2003b). The constant b was estimated at 0.55 (± 0.1) and α at 11 rock falls/yr (between 11×0.5 and 11×2). The volumetric erosion rate of the cliff can be obtained by integration of Eq. (1) (Hantz et al., 2003a), and divided by the wall area to give the linear rate of retreat. The value obtained of $1.5\,mm\,yr^{-1}$ is compatible with the retreat of the Urgonian seam, which is around 10 km in 10^7 yr. Assuming the rock fall frequency is constant with time, the mean age of the wall can be estimated to 5500 yr. This value is compatible with the first results obtained by cosmic ray surface exposure dating, which give a mean age of 8000 yr (Hantz and Frayssines, 2007).

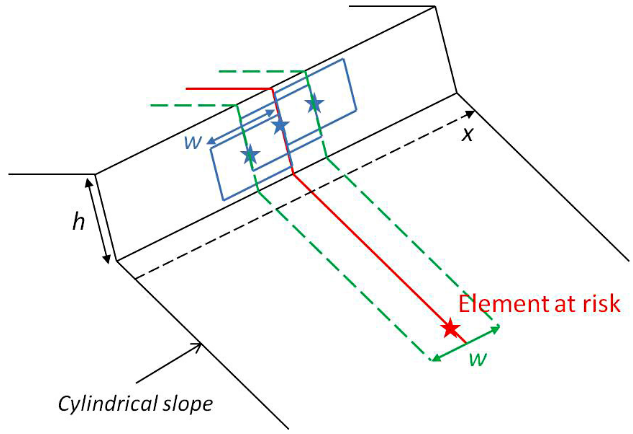

Fig. 1. Cylindrical slope with rock compartments having the same width w.

The spatial temporal rock fall frequency (F_{st}) is the number of rock falls per unit of time and per unit of wall area, with a volume greater than a given value V (in m^3), expressed by:

$$F_{st} = a V^{-b} \tag{2}$$

where a = number of rock falls, per unit of time and area, with volume greater than $1\,m^3$ ($a = \alpha$/wall area).

3 Failure frequency and failure probability in a homogenous rock wall

Let us consider a homogenous rectilinear wall the height of which is h, and define a horizontal abscissa x, which is parallel to contour lines (Fig. 1). The underlying slope is supposed to be cylindrical. A rock mass falling from this wall in a single rock fall event will be called a rock compartment. We first assume that the falling compartments have a constant width, w (defined parallel to x). For a profile of the wall to be affected by a rock fall, the centre of gravity of the potentially unstable rock compartment must have an abscissa between $(x - w/2)$ and $(x + w/2)$, i.e. it must be in a vertical wall slice the width of which is w (Fig. 1). This assumption neglects the lateral dispersion which always occurs for an actual rock fall, and then leads to underestimating the frequency. The frequency of the rock falls which affect any profile of the wall is then $F_{st}hw$. In the same way, the frequency of the rock falls of width w which affect a slice of the wall of width v is $F_{st}h(w + v)$.

We now consider that the width of the falling compartments is not constant anymore, and the volumes of the falling compartments are distributed according to Eq. (1). To determine the fall frequency affecting any profile of the wall, one must consider a slice of wall the width of which equals the width of the fallen compartment (Fig. 1), which is not constant anymore and is related to its volume. The relation between the volume and the width of the falling compartments depends on the internal structure of the rock wall. Frayssines and Hantz (2006) have analyzed the relationship between the width, the length (measured in the movement direction), and the thickness of compartments fallen from the calcareous cliffs of the Grenoble area. It appears that the length is about twice the width, which in turn is 4 times the thickness. In a general formulation, the relationship between the volume (V) and the width (w) of the fallen compartments may be written:

$$V = kw^3 \tag{3}$$

where k is a shape factor, which equals 0.5 for the calcareous cliffs of the Grenoble area. If k is unknown, the author recommends using the value of 1.

For compartments the volume of which is between V and $(V + dV)$, the fall frequency affecting a profile of the wall can be calculated as below, using Eqs. (2) and (3):

$$\begin{aligned} dF &= hw\,|dF_{\mathrm{st}}| = -h\left(\frac{V}{k}\right)^{1/3} d\left(aV^{-b}\right) \\ &= abhk^{-1/3}V^{-b-2/3}dV \end{aligned} \tag{4}$$

The integration of Eq. (4) gives the frequency of the rock falls the volume of which is between $V_{\min}$ and $V_{\max}$:

$$F_{\mathrm{f}} = \frac{3abhk^{-\frac{1}{3}}}{3b-1}\left(V_{\min}{}^{\left(\frac{1}{3}-b\right)} - V_{\max}{}^{\left(\frac{1}{3}-b\right)}\right) \tag{5}$$

Note that, as b is higher than 1/3, the limit of F_{f}, as $V_{\min}$ approaches 0, is infinite. This is not a problem because we always consider a minimal volume for the rock falls. On the contrary, the limit of F_f, as $V_{\max}$ approaches infinity, is not infinite. This allows taking into account the largest rock falls which can occur in the wall considered. The largest possible volume depends essentially on the height of the wall, but is very difficult to estimate. Fortunately, the exponent of $V_{\max}$ in Eq. (5) is about 0.2 and, consequently, the frequency is not very sensitive to this parameter. It is also not sensitive to the parameter k, the exponent of which is 1/3. Assuming k can range between 0.4 and 2, $k^{1/3}$ varies between 0.74 and 1.26. Considering that the precision which can be hoped for the failure probability is by a factor 10, taking 1 for the value of k appears to be acceptable.

We now consider an element at risk, the width of which is v. It can be seen in Figs. 1 and 2, that for the element to be affected by a rock fall of width w, the centre of gravity of the potentially unstable rock compartment must be in a vertical wall slice, the width of which is $(v + w)$. The fall frequency affecting this slice of wall can be obtained by substituting w by $(v + w)$ in Eq. (4). Thus, the frequency is:

$$\begin{aligned} F_{\mathrm{f}} = &\frac{3abhk^{-\frac{1}{3}}}{3b-1}\left(V_{\min}{}^{\left(\frac{1}{3}-b\right)} - V_{\max}{}^{\left(\frac{1}{3}-b\right)}\right) \\ &+ ahv\left(V_{\min}{}^{-b} - V_{\max}{}^{-b}\right) \end{aligned} \tag{6}$$

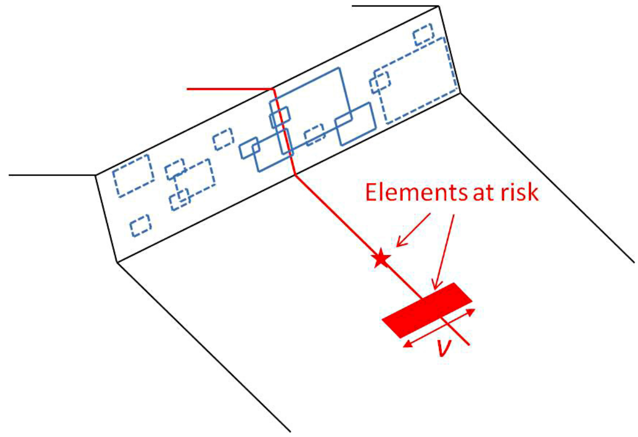

Fig. 2. Cylindrical slope featuring both types of elements at risk (punctual and with a width v) and rock compartments having different widths. The compartments threatening the element at risk with width v are in solid lines.

The problem of the temporal distribution of landslides has been discussed by Durville (2004). Rat (2006) has shown that the occurrence of rock falls on a road in the Réunion Island is well described by the Poisson's law, provided one considers time steps of more than 5 days. Assuming the Poisson's law to describe the temporal occurrence of rock falls, the probability for a slice of wall the width of which is v, to be affected by at least one rock fall during a period of time t is:

$$P_{\mathrm{f}} = 1 - e^{-F_{\mathrm{f}}\,t} = 1 - e^{-\frac{t}{T_{\mathrm{f}}}} \tag{7}$$

where $T_{\mathrm{f}} = 1/F_{\mathrm{f}}$ is the return period of the rock falls. If the period considered is small compared to the return period T_{f}, the failure probability P_{f} can be approximated by:

$$P_{\mathrm{f}} = F_{\mathrm{f}}\,t = t/T_{\mathrm{f}} \tag{8}$$

Note that the failure frequency and the failure probability given by Eqs. (6) and (7) are estimates of the hazard if the element at risk is close enough to the rock wall so that the probability of propagation equals 1.

4 Frequency and probability of reach by a fall with a minimal energy

We now consider an element at risk, the width of which is v, located at (or near) the foot of a rock wall and which is necessarily reached by a rock fall affecting the overlying slice of rock wall having the same width v (it is assumed that the element is sufficiently high not to be flown over by the blocks). It means that the propagation probability equals 1 and, consequently, the hazard equals the failure probability, which is given by Eq. (7). The same is true of the frequency, which equals the failure frequency given by Eq. (6). Moreover, it is assumed that the kinetic energy E of a compartment reaching the foot of the rock wall is given by its initial potential energy:

$$E = \gamma V h \tag{9}$$

where γ is the specific weight of the rock, V the volume of the compartment, and h its initial height, taking as a reference the height the wall foot.

In the context of risk assessment, the events to consider are rock falls whose kinetic energy exceeds a given value E_0 when they reach the element at risk. This value depends on the type of element at risk. For example, the Swiss federal guidelines (Lateltin et al., 2005) consider that a reinforced concrete wall can resist to an impact energy of 300 kJ.

Let us first assume that the falling compartments have the same width (w) and consequently the same volume (V) according to Eq. (3). For a point located at the foot of the rock wall, at the abscissa x, to be reached by a rock fall (the energy of which is higher than E_0), the center of gravity of the falling mass must be initially located at an abscissa between $(x - w/2)$ and $(x + w/2)$, and at a height greater than h_0 given by:

$$h_0 = \min\left(H, \frac{E_0}{\gamma V}\right) \tag{10}$$

where H is the height of the rock wall (Fig. 3). The frequency for the point considered, with an energy higher than E_0, is then:

$$F_\mathrm{r}(E_0) = F_\mathrm{st}\, w(H - h_0) \tag{11}$$

Now considering compartments whose volume is between V and $(V + dV)$, the frequency for an element at risk whose width is v, with energy higher than E_0, is given by:

$$dF_\mathrm{r} = (w + v)(H - h_0)dF_\mathrm{st} \tag{12}$$

This frequency cancels if $\gamma V h$ is lower than E_0, i.e. if V is lower than $E_0/\gamma H$. Then the integration of Eq. (12) must be done from $V_\mathrm{min} = E_0/\gamma H$. The frequency which is obtained is lower than the failure frequency F_f given by Eq. (6):

$$F_\mathrm{r} = F_\mathrm{f} - \frac{3abk^{-\frac{1}{3}}E_0}{\gamma(3b+2)}\left({V_\mathrm{min}}^{-b-\frac{2}{3}} - {V_\mathrm{max}}^{-b-\frac{2}{3}}\right) - \frac{abvE_0}{\gamma(b+2)}\left({V_\mathrm{min}}^{-b-1} - {V_\mathrm{max}}^{-b-1}\right) \tag{13}$$

with

$$V_\mathrm{min} = E_0/\gamma H \tag{14}$$

Note that the energy loss due to rebounds on the rock wall is not considered here. So Eq. (13) overestimates the frequency.

Assuming the occurrence of the rock falls is given by Poisson's law, the hazard P_r is given by the expression:

$$P_\mathrm{r} = 1 - e^{-F_\mathrm{r}\, t} = 1 - e^{-\frac{t}{T_\mathrm{r}}} \tag{15}$$

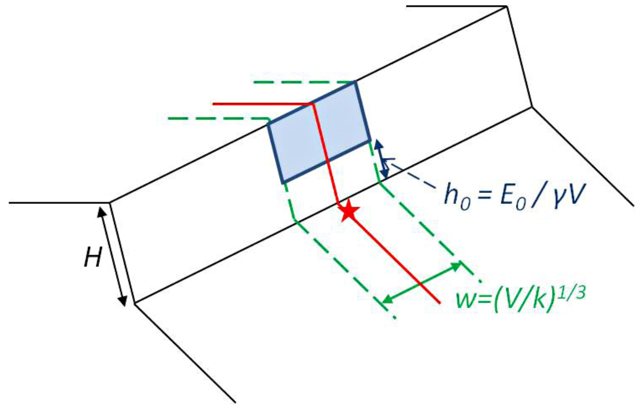

Fig. 3. Cylindrical slope with a punctual element at risk (star). The solid rectangle represents the wall area to be considered for a rock volume V to have a minimal potential energy E_0. γ: the specific weight of the rock; k: shape factor.

5 Discussion

5.1 Homogenous rock wall

The initial hypothesis of a homogenous rock wall may be oversimplified in some cases. If the failure frequency varies along the wall, it is the same for the hazard. In the case of a fix element at risk (a house for example), the hazard depends on its abscissa x (Fig. 1). However, the method presented allows estimating the order of magnitude of the hazard in the cases where it is not possible to distinguish particularly hazardous sections of the wall.

When the element at risk is moving (a vehicle for example), the hazard during the time the risk element traverses the whole wall is not affected by the x variations of the failure frequency (the most hazardous sections are compensated by the least ones).

5.2 Cylindrical slope

The hypothesis of a cylindrical slope is also a simplification. In the general case of a 3-D non-cylindrical slope (Fig. 4), the above given frequencies are average values along the contour lines of the slope. In drainage ways, the actual frequencies are higher than the average value, and they are lower on the divides. For a given element at risk, Fig. 4 shows the wall area that must be considered to determine the hazard. In Eq. (6), v must be substituted, for good measure and protection purposes, by the width of the wall section threatening the element at risk (Fig. 4). Note that the failure frequency given by Eq. (6) and (13) gives the hazard only if the element at risk is close enough to the rock wall so that the probability of propagation equals 1. Otherwise the probability of propagation must be taken into account (see for example Guzzetti et al., 2002; Jaboyedoff et al., 2005).

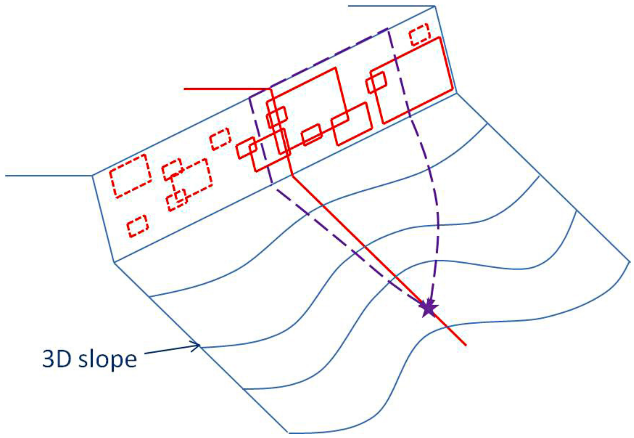

Fig. 4. 3-D slope with a punctual element at risk (star). The dashed line represents the area where a rock compartment must start to threaten the element at risk.

5.3 Fragmentation of the rock falls

The impact frequency given by Eq. (13) concerns rock falls with very different sizes, which can imply one or several blocks. For rock falls implying several blocks, the element at risk does not receive all the energy. This leads to an overestimation of the hazard with a given energy. For a better estimation, the individual block frequency rather that the rock fall frequency must be considered. A method to derive the block frequency from the rock fall event frequency is given by Corominas (2005), based on the analysis of the distribution of block volumes on talus slopes. This kind of information should be very useful in the future rock fall inventories. Note that when the considered minimal energy is low (as in the following application), most of the rock falls considered are small and consist of single blocks.

6 Application to a hiking track at the foot of a cliff

6.1 Hazard assessment

The method has been applied to the hiking track which stretches over 1 km along the base of the Saint-Eynard calcareous cliff, near Grenoble (Fig. 5). The height of the cliff is about 150 m. The spatial temporal failure frequency is well described by Eq. (2), where the parameters a and b have been determined from an inventory concerning 120 km of cliff (Sect. 2). The width of the element at risk (hiker) was set to 0.5 m. The minimal energy considered (0.025 kJ) was derived from climbing helmet tests. To reach this energy level, the rock compartments detaching from the top of the cliff must have a minimal volume of 6×10^{-6} m^3 (Sect. 4), which corresponds to a width of 2.3 cm (Eq. 3). This minimal volume increases when the detachment point moves down the wall, as shown in Table 1. It was assumed that Eq. (2) applies

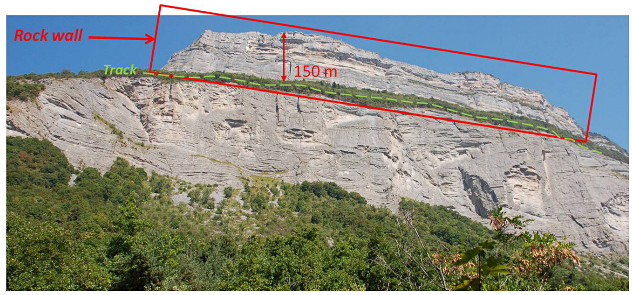

Fig. 5. Saint-Eynard calcareous cliff, near Grenoble.

to rock volumes as small as 10^{-6} m^3, as expected from the results obtained by Dewez et al. (2009). These authors have observed rock falls with volumes from 10^{-4} to 10^{+4} m^3 in a chalk cliff, and have obtained a b value of 0.51 very close to the value of 0.55 ($\pm$0.1) obtained for the limestone cliffs in the Grenoble area for volumes ranging from 10^2 to 10^7 m^3. This suggests that for calcareous rocks, the power law could be valid for a very large volume range. A sensitivity analysis has been achieved taking account of the uncertainty affecting the parameters a and b. The impact frequencies with a minimal energy of 0.025 kJ have been calculated using Eq. (13) and are given in Table 2.

According to the uncertainties affecting a and b, the frequency was determined with an uncertainty factor of 10. The central value is 2.3×10^{-2} events per year, which gives a return period of 44 yr.

It has been mentioned in Sect. 3 that the frequency is not very sensitive to the value estimated for the maximal possible rock fall volume. This statement is confirmed in the case presented: The 2-digit values given in Table 2 are valuable for any maximal volume larger than 100 m^3. In the present case, the maximal possible rock fall volume was obviously larger than 100 m^3. It can also be seen from Eq. (5) that the smaller the minimal volume considered, the lower the contribution of the largest volumes.

6.2 Risk assessment

The time necessary for a hiker to cover the route is about one hour. As this time is small compared to the return period of the rock falls (tens of years from Table 2), the probability for a period of one hour can be approximated by Eq. (8) with the frequency given in Table 2 (Eq. 8 applies for the hazard as well as for the failure probability). With an annual frequency of 2.3×10^{-2}, the probability obtained is about 2.6×10^{-6}. Assuming that a hiker wearing a helmet is killed if he is affected by a fall whose energy is higher than 0.025 kJ, a hiker who takes the trail once a year increases his/her yearly death probability by about 10^{-6}. This individual risk has to be compared with the yearly death rate in France, which varies from 10^{-4} (for a 10 yr old child) to 10^{-2} (for a 65 yr old adult). Acceptable and tolerable individual life risk criteria

Table 1. Minimal volume and corresponding width to consider for a rock compartment reaching a wall foot with a minimal kinetic energy of 0.025 kJ, as a function of the detachment height.

Height (m)	150	100	50	30	15
Volume (m^3)	6.2×10^{-6}	9.3×10^{-6}	1.9×10^{-5}	3.1×10^{-5}	6.2×10^{-5}
Width (m)	0.023	0.026	0.033	0.040	0.050

Table 2. Impact frequency (event per year) with a minimal kinetic energy of 0.025 kJ, of an element at risk of width 0.5 m, located at the foot of the 150 m high Saint-Eynard rock cliff.

a (10^{-7} fall/yr m^2)	2.3	4.7	9.4
$b = 0.45$	3.8×10^{-3}	7.7×10^{-3}	1.5×10^{-2}
$b = 0.55$	1.1×10^{-2}	2.3×10^{-2}	4.5×10^{-2}
$b = 0.65$	3.5×10^{-2}	7.1×10^{-2}	1.4×10^{-1}

in different countries are reported by Leroi et al. (2005). The individual risk of about 10^{-6} corresponds to the broadly acceptable limit given by the Health and Safety Executive (UK) for land use planning around industries. As higher risks are usually accepted from naturally occurring landslides than from engineered slopes, and as the hazard had been overestimated (Sect. 5), this risk can be considered as acceptable.

In terms of societal risk, considering that about one thousand hikers take this trail each year, the expected annual number of deaths is about 10^{-3}. From the knowledge of the author, no death has occurred on this trail, which had been taken by hikers for several decades before it was closed after two rock falls of some tens of m^3 occurred in 2003 and 2006. Leroi et al. (2005) have reviewed published societal life risk criteria. HKSAR (Hong Kong Special Administrative Region) has published interim risk guidelines especially for natural slopes. The societal risk of about 10^{-3} corresponds to their limit between the unacceptable risk and the tolerable risk. As the hazard had been been overestimated (Sect. 5), it can be considered as tolerable by society. That said, according to IUGS (1997), a tolerable risk should, wherever reasonably practicable, be reduced.

7 Conclusions

The method presented allows estimating the hazard and impact frequency at the foot of a homogenous cliff, with an uncertainty factor of 10, from a historical rock fall inventory.

If the cliff is not homogenous, the obtained frequency represents only an average value along a contour line. In this case the actual frequency for a fix element at risk may greatly differ from this value. If the slope under consideration differs significantly from a cylindrical slope, the obtained frequency also represents an average value along a contour line. However, in both cases of non-homogenous walls and non-cylindrical slopes, the obtained frequency is pertinent for a moving element at risk (pedestrian or vehicle).

The method proposed to determine the rockfall frequency with a minimal energy leads to an overestimation of the hazard. Individual block frequency rather than rock fall frequency must be considered for a better estimation.

Hazard and risk have been estimated for the Saint-Eynard cliff. With the available data, the individual risk can be considered as acceptable, and the societal risk as tolerable.

Rock fall inventories at different spatial and temporal scales featuring the location, date, volume of the falls, and the dimensions of the fallen compartments (width, length, and thickness), together with a better knowledge of the rate of retreat of the rock walls, are needed for better estimating of hazard and risk.

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