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A probabilistic method to assess rockfall risk on mountaineering trail: the Couloir du Goûter study case / Marchelli, M., De Biagi, V., Peila, D.. - ELETTRONICO. - (2024), pp. 1-4. (International Landslides Symposium 2024 Chambéry (Fr) 8-12/07/2024).

*Availability:*

This version is available at: 11583/2991166 since: 2024-07-25T00:43:18Z

*Publisher:*

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## A probabilistic method to assess rockfall risk on mountaineering trail: the Couloir du Goûter study case

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2 **SUMMARY:** Rockfall represents one of the most crucial hazards in mountain environment.  
3 Global warming and climate change increase the frequency and the altitude at which events  
4 occur, increasing the number of fatal accidents or injuries on mountaineering trail paths. To  
5 predispose effective actions, a quantification of the risk in terms of annual probability of death  
6 for hikers becomes an urgent issue. A quantitative risk assessment method based on event tree  
7 analysis, tailored for the specific case, is proposed and applied to the study case of the Couloir  
8 du Goûter, one of the most critical points of the ascent to Mont Blanc.

9  
10 **Keywords:** rockfall risk, mountaineering trail, event tree analysis

### 11 **Introduction**

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13  
14 Climate trends indicate that natural hazards are expected to increase as a result of global  
15 warming, underlining the urgency for accurate risk assessment and management. Among all  
16 natural hazards, rockfall represent one of the most dangerous and its spatial and temporal  
17 frequencies are expected to increase due to permafrost and rock degradation and massive  
18 glaciers retreat (Knoflach et al., 2021; Mirhadi & Macciotta, 2023). The growing number of  
19 people in mountain regions, and thus of people doing mountaineering activities, increase the  
20 vulnerability of high-mountain areas and mountaineering trails, underlining the urgency for an  
21 accurate rockfall risk assessment to predispose effective mitigation strategies.

22 A quantification of the possible damages, particularly in terms of annual probability of death,  
23 is often required by Authorities to manage the risk and measure the effectiveness of the  
24 mitigation measures. This means that detailed information and accurate analyses on events  
25 occurrence probability and their propagation are required, together with the characteristics of  
26 the elements at risk. Being people movable elements at risk, their exposure represents one of  
27 the most important parameters, whose proper evaluation could be very difficult in  
28 mountaineering trail, where climbing could be in teams roped up together or alone and in which  
29 climbing time could vary significantly during the path.

30 A method tailored to hikers on mountaineering trail is herein presented. The proposed method  
31 accounts for all the possible scenarios leading to a fatal event or injury and is based on a mixed  
32 formulation of the Quantitative Risk Assessment and the Event Tree Analysis approaches,  
33 firstly developed for vehicular traffic road (Marchelli et al., 2021). The proposed method is  
34 applied to the study case of the Couloir du Goûter, one of the most critical points of the ascent  
35 to Mont Blanc on the French Normal Route, popularly known as the "Couloir of Death".

### 36 **Methodology**

37  
38  
39 Rockfall is generally considered as a Poisson point process phenomenon, in which the events  
40 are independent, with an average frequency of occurrence according to their magnitude (De  
41 Biagi, 2017). Assuming the exposed area consisting of  $q$  elements at risk and  $p$  different rock  
42 block volumes that can detach, the risk  $R$  is computed as (Corominas et al., 2005):



$$R = \sum_{l=1}^p \sum_{m=1}^q (P_T^l P_S^{l,m} E^m V^{l,m} W^m) \quad (1)$$

43 where  $P_T^l$  is the detachment probability, i.e. the frequency associated to the possible  $l$  released  
44 volume,  $P_S^{l,m}$  is the spatial probability that this block reaches the  $m$ -th element at risk, and  $E^m$ ,  
45  $V^{l,m}$ ,  $W^m$  are the exposure, the vulnerability, and the value, respectively. The exposure  
46 represents the probability that the elements are exposed to potential loss, while vulnerability is  
47 the degree of loss, when a phenomenon of given intensity occurs. The detachment probability  
48 depends on several factors, i.e. lithology, orientation and structural configuration of the  
49 discontinuities sets on the rock face, degree of weathering, freeze-thaw cycles, other external  
50 factors, e.g. seismic actions or wildfires (Pérez-Rey et al., 2019). Nevertheless, due to the  
51 complexity and the uncertainties related to the data, the definition of  $P_T^l$  is often based on  
52 statistics of past events. In case of mountaineering trail,  $P_S^{l,m}$  can be referred to the system on  
53 which the elements at risk ( $P_S^l$ ), i.e. hikers, are moving, i.e. the path. As people are the element  
54 at risk, the vulnerability could be considered magnitude-independent, assuming that every block  
55 of any volume, can cause a fatality. Thus, the correlation between release volume and frequency  
56 can be neglected and  $P_T^l$  can be estimated as the mean annual frequency of event  $N_y$  with any  
57 volume. If  $N_y \geq 0.5$ , Eq. (1) returns in:

$$R = 1 - \left( 1 - \sum_{m=1}^q (E^m V^{l,m} W^m) \right)^{N_y P_S^{l,m}} \quad (2)$$

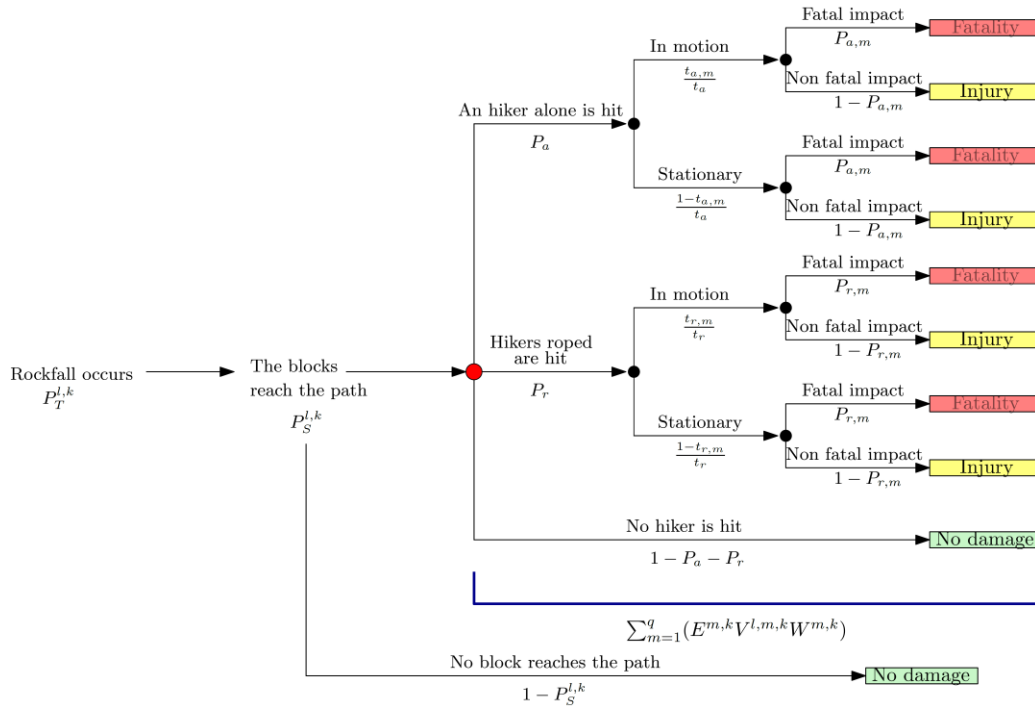
58 In principle, different source areas can be individuated, as well as different hiking conditions,  
59 i.e. climbers roped together or alone. Subdividing the path into portions equal for number of  
60 source areas insisting on it and hiking conditions, it results:

$$R = \sum_{k=1}^n P_T^{l,k} P_S^{l,k} \left[ \sum_{m=1}^q (E^{m,k} V^{l,m,k} W^{m,k}) \right] \quad (3)$$

61 in which as  $P_S^{l,k}$  can vary along the  $k$ -th portion; thus, a homogenization process is required. To  
62 evaluate the term  $\sum_{m=1}^q (E^{m,k} V^{l,m,k} W^{m,k})$ , for each  $k$ -th portion a method based on event tree  
63 analysis approach (ETA) has been developed by the Authors (Marchelli et al., 2021). The ETA  
64 is a logical procedure in which, starting from a single initiating event, in this case the arrival of  
65 a block on the path, and defining all the possible mutually exclusive options which can occur,  
66 all the possible scenarios are individuated and their probabilities of occurrence are computed.  
67 Each possible outcome probability is given by the conditional probability along its own  
68 pathway, while the probability of more outcomes is given by the sum of the probabilities of  
69 each outcome. The monetary value associated to death is neglected in the analysis. Once  
70 obtained  $\sum_{m=1}^q (E^{m,k} V^{l,m,k} W^{m,k})$  as the probability of having at least one fatality due to the  
71 certain occurrence of an event, this must be inserted into Eq. (3) to consider the temporal and  
72 spatial variabilities of the events. Figure 1 displays the procedure to compute the risk  $R$  for each  
73  $k$ -th portion with the proposed event tree. Referring to this last, a probability is associated to  
74 each branch of the tree. Several hiking conditions are considered: (i) hikers alone or roped up,  
75 (ii) moving in the hazardous area or stationary (i.e. as climbing a vertical rock face just under  
76 the potential source zone or at rest). For the latter aspect the probability is computed knowing  
77 the expected total time for travelling the portion and the resting time. The probability that hikers  
78 are hit by the block is derived knowing their spatial and temporal probability that they are in



79 the investigated section. Trajectory analyses can be used both to evaluate  $P_S^{l,k}$  and the expected  
 80 kinetic energies to estimate whether the impact is fatal.



81  
 82 Figure 1: Event tree procedure for rockfall risk on mountaineering trail

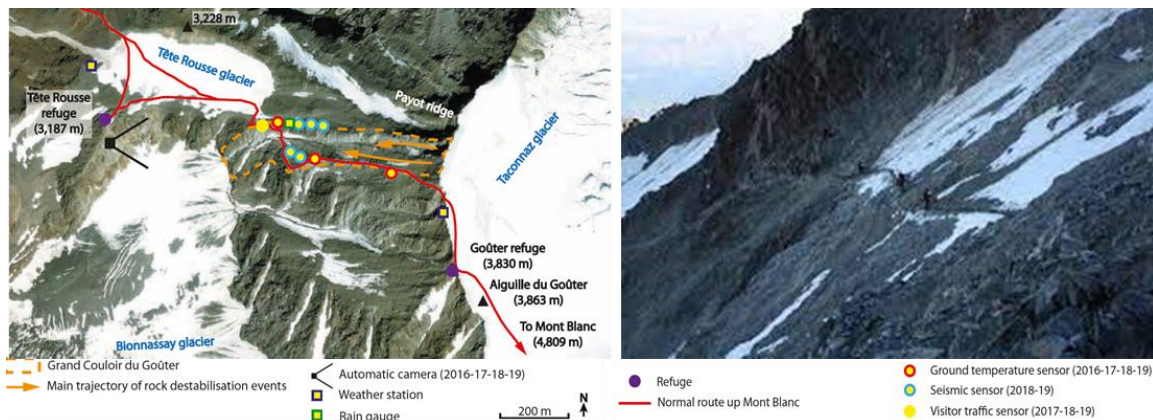
83  
 84 **Case study**

85  
 86 The proposed procedure (refer to Figure 1 for the notation) is applied to the particular case of  
 87 the Couloir du Gôûter, one of the most beloved but dangerous mountaineering routes, climbed  
 88 by about 17000 mountaineers per year (Figure 2). Due to its topographical and geological  
 89 features, the Couloir du Gôûter is particularly suitable for rock destabilization and consequent  
 90 rockfall events: the intense degree of fracturation, enhanced by daily freeze-thaw cycling and  
 91 meltwater refreezing, together with abundant water infiltration, due to increasing snow melt  
 92 and liquid precipitations, result in frequent rockfall detachments (Mourey et al., 2021). Bet-  
 93 tween 1990 and 2017, 387 incidents were recorded, of which 122 in the traverse across the  
 94 couloir, and mainly due to rockfall (79%). Referring to those in the crossing, about 25% were  
 95 fatal and the remaining with injuries (Mourey et al., 2022). Due to this, a huge monitoring  
 96 campaign was conducted between 2018 (26 days) and 2019 (68 days) (Mourey et al., 2022) in  
 97 which rockfall phenomena and associated energies were hourly recorded together with the  
 98 numbers of climbers. A digital camera and a seismic network were used for detecting rockfalls  
 99 and characterising their energy, while traffic sensors to record passages. Weather sensors were  
 100 installed for finding correlations with events (Figure 2). The selected period was summer only,  
 101 i.e. when the Couloir is generally climbed. In this period, a total of 747 events were recorded  
 102 (28 events/day in 2018 and 39 events/day in 2019), mainly in the afternoon, with mean and  
 103 maximum energies of 160 and 4000 kJ, respectively, i.e. much greater than the maximum  
 104 energy absorbed by a helmet, i.e. 100 J. A total of 21 000 ascending-descending passages were  
 105 recorded, mainly between 9.00 am and 3.00 pm and almost all not roped up, i.e.  $P_a$  equal to 1.  
 106 This campaign allows calculating the mean number of passages and expected events, i.e.  $P_T^{l,k}$ ,  
 107 for each hour in a day. The risk is thus calculated hourly. The potential source areas insist on a  
 108 100 m horizontal mountain pass, generally hiked without stationary phase, i.e.  $t_{a,m} = t_a$  of  
 109 about 2 minutes. Due to the verticality of the rock face,  $P_S^{l,k}$  can be considered equal to 1. To



110 compute the yearly risk, only the effective days of possible climbing are considered. Hence, the  
111 obtained annual risk is equal to  $5.713 \cdot 10^{-3}$ , while the daily risk is  $1.566 \cdot 10^{-5}$ .

112



113

114 Figure 2: Study site and monitoring system (adapted by Mourey et al., 2021 and Matt Charland / Fondation Petzl)

115

## 116 Conclusion

117

118 The study proposes a method to address the risk due to rockfall on mountaineering routes,  
119 considering the possible hiking/climbing configurations that occur in such outdoor activity. The  
120 profitability of the method has been investigated applying it to the study case of the Couloir du  
121 Goûter. Thanks to a detailed monitoring campaign, all the required input data are derived and  
122 an annual risk in terms of probability of fatal accident is calculated. The method can be used by  
123 Authorities to evaluate the priority of intervention and predispose effective mitigation plans.

124

## 125 Acknowledgment

126

127 This study was carried out within the RETURN Extended Partnership and received funding  
128 from the European Union Next-GenerationEU (National Recovery and Resilience Plan –  
129 NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

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