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

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

Keywords: rockfall risk, mountaineering trail, event tree analysis

Introduction

Climate trends indicate that natural hazards are expected to increase as a result of global warming, underlining the urgency for accurate risk assessment and management. Among all natural hazards, rockfall represent one of the most dangerous and its spatial and temporal frequencies are expected to increase due to permafrost and rock degradation and massive glaciers retreat (Knoflach et al., 2021; Mirhadi & Macciotta, 2023). The growing number of people in mountain regions, and thus of people doing mountaineering activities, increase the vulnerability of high-mountain areas and mountaineering trails, underlining the urgency for an accurate rockfall risk assessment to predispose effective mitigation strategies.
A quantification of the possible damages, particularly in terms of annual probability of death, is often required by Authorities to manage the risk and measure the effectiveness of the mitigation measures. This means that detailed information and accurate analyses on events occurrence probability and their propagation are required, together with the characteristics of the elements at risk. Being people movable elements at risk, their exposure represents one of the most important parameters, whose proper evaluation could be very difficult in mountaineering trail, where climbing could be in teams roped up together or alone and in which climbing time could vary significantly during the path.
A method tailored to hikers on mountaineering trail is herein presented. The proposed method accounts for all the possible scenarios leading to a fatal event or injury and is based on a mixed formulation of the Quantitative Risk Assessment and the Event Tree Analysis approaches, firstly developed for vehicular traffic road (Marchelli et al., 2021). The proposed method is applied to the study case of the Couloir du Goûter, one of the most critical points of the ascent to Mont Blanc on the French Normal Route, popularly known as the "Couloir of Death".

Methodology

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

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

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

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

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

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

in which as $P_S^{l,k}$ can vary along the k-th portion; thus, a homogenization process is required. To 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 analysis approach (ETA) has been developed by the Authors (Marchelli et al., 2021). The ETA is a logical procedure in which, starting from a single initiating event, in this case the arrival of a block on the path, and defining all the possible mutually exclusive options which can occur, all the possible scenarios are individuated and their probabilities of occurrence are computed. Each possible outcome probability is given by the conditional probability along its own pathway, while the probability of more outcomes is given by the sum of the probabilities of each outcome. The monetary value associated to death is neglected in the analysis. Once 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 certain occurrence of an event, this must be inserted into Eq. (3) to consider the temporal and spatial variabilities of the events. Figure 1 displays the procedure to compute the risk R for each k-th portion with the proposed event tree. Referring to this last, a probability is associated to each branch of the tree. Several hiking conditions are considered: (i) hikers alone or roped up, (ii) moving in the hazardous area or stationary (i.e. as climbing a vertical rock face just under the potential source zone or at rest). For the latter aspect the probability is computed knowing the expected total time for travelling the portion and the resting time. The probability that hikers are hit by the block is derived knowing their spatial and temporal probability that they are in the investigated section. Trajectory analyses can be used both to evaluate $P_S^{l,k}$ and the expected kinetic energies to estimate whether the impact is fatal.

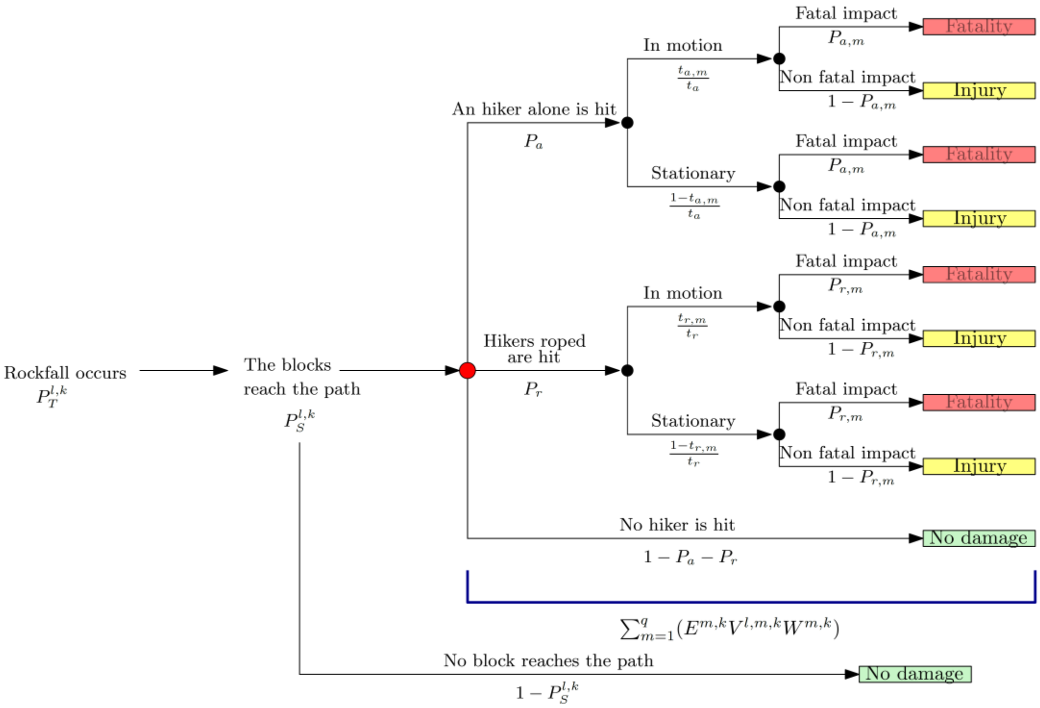

Figure 1: Event tree procedure for rockfall risk on mountaineering trail

Case study

The proposed procedure (refer to Figure 1 for the notation) is applied to the particular case of the Couloir du Goûter, one of the most beloved but dangerous mountaineering routes, climbed by about 17000 mountaineers per year (Figure 2). Due to its topographical and geological features, the Couloir du Goûter is particularly suitable for rock destabilization and consequent rockfall events: the intense degree of fracturation, enhanced by daily freeze-thaw cycling and meltwater refreezing, together with abundant water infiltration, due to increasing snow melt and liquid precipitations, result in frequent rockfall detachments (Mourey et al., 2021). Between 1990 and 2017, 387 incidents were recorded, of which 122 in the traverse across the couloir, and mainly due to rockfall (79%). Referring to those in the crossing, about 25% were fatal and the remaining with injuries (Mourey et al., 2022). Due to this, a huge monitoring campaign was conducted between 2018 (26 days) and 2019 (68 days) (Mourey et al., 2022) in which rockfall phenomena and associated energies were hourly recorded together with the numbers of climbers. A digital camera and a seismic network were used for detecting rockfalls and characterising their energy, while traffic sensors to record passages. Weather sensors were installed for finding correlations with events (Figure 2). The selected period was summer only, i.e. when the Couloir is generally climbed. In this period, a total of 747 events were recorded (28 events/day in 2018 and 39 events/day in 2019), mainly in the afternoon, with mean and maximum energies of 160 and 4000 kJ, respectively, i.e. much greater than the maximum energy absorbed by a helmet, i.e. 100 J. A total of 21 000 ascending-descending passages were recorded, mainly between 9.00 am and 3.00 pm and almost all not roped up, i.e. P_a equal to 1. This campaign allows calculating the mean number of passages and expected events, i.e. $P_T^{l,k}$, for each hour in a day. The risk is thus calculated hourly. The potential source areas insist on a 100 m horizontal mountain pass, generally hiked without stationary phase, i.e. $t_{a,m} = t_a$ of about 2 minutes. Due to the verticality of the rock face, $P_S^{l,k}$ can be considered equal to 1. To compute the yearly risk, only the effective days of possible climbing are considered. Hence, the obtained annual risk is equal to $5.713 \cdot 10^{-3}$, while the daily risk is $1.566 \cdot 10^{-5}$.

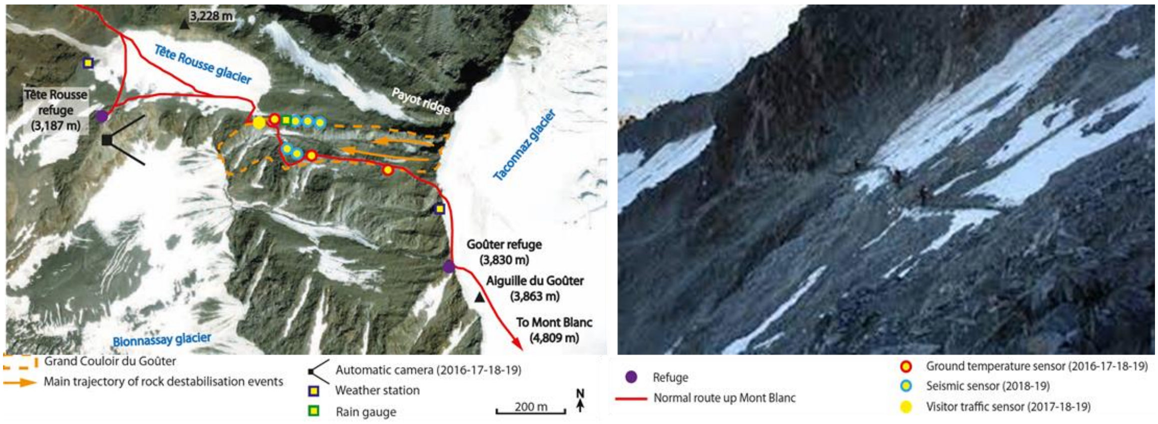

Figure 2: Study site and monitoring system (adapted by Mourey et al., 2021 and Matt Charland / Fondation Petzl)

Conclusion

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

Acknowledgment

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

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