An Efficient Reliability-based Design Approach to Reduce Rockfall Risk Below a Target Threshold

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Rockfalls are expected to increase due to global warming and extreme events induced by climate change. An accurate quantification of the risk is fundamental for Administrations to predispose effective risk mitigation plans. Risk value should account for all the possible events that can occur in a specific time, i.e. for a magnitude (block volume) frequency relationship. Among structural protective measures, rockfall barriers are widely selected. Despite their design method has been almost defined, even not standardized, the widely adopted safety factors approach with fixed factors does not allow obtaining a specific probability of failure. Moreover, the event magnitude-frequency relationship is not accounted. A novel time-independent reliability-based approach has been recently conceived by the Authors, allowing obtaining the design values for a specific failure probability. The method accounts for all the possible events, integrating them in time with their probability. In this way, an increase of rockfall events can been accurately considered. The obtained barrier failure probability can be used to compute the risk reduction in a given time or, conversely, to define the maximum failure probability of a barrier that could be accepted.

Keywords: rockfall risk, reliability design, magnitude-frequency, risk analysis

Introduction

Climate change and environmental degradation are existing threats to Europe and worldwide, and adaptation to climate change is becoming crucial in the next future. Permafrost and rock degradation, and massive glaciers retreat by global warming effects of climate change have a direct impact on mountain areas, with a significant increase of rockfall phenomena (Knoflach *et al.*, 2021). Rockfall occurrence has increased its frequency, and climate trends indicate that rockfall events are expected to rise throughout the foreseeable future (Hartmeyer *et al*, 2020). The growing number of people and infrastructure in mountain regions increment the vulnerability of high-mountain areas, underlining the urgency for both an accurate rockfall risk assessment and effective risk mitigation strategies. A quantification of the risk is often required by Authorities to manage the risk predisposing effective mitigation plans, meaning that accurate hazard and consequences analyses have to be performed. The analysis starts from the identification and characterization of the possible initiating events, defining one or more realistic scenarios, from which propagation analyses have to be performed. As for other natural hazards, events differing for magnitudes, i.e. for rockfall the block volume, can occur with different probabilities. Even difficult, a method to estimate the return period of each possible volume has been proposed (De Biagi *et al.*, 2017; Moos *et al.*, 2022), and the profitability of rock-face monitoring systems has been widely assessed (Giacomini *et al.*, 2020).

Propagation analyses and hazard computation have to performed for each possible volume, which is characterized by a specific frequency (Lari *et al.*, 2014; Farvacque *et al.*, 2021). For each event, given the element at risk, the consequences have to be computed to obtain the risk value. When this value is higher than an acceptable threshold, mitigation measures have to be adopted. Among structural mitigation measures, and particularly among protective ones, net

fences (i.e. flexible rockfall barriers) are about the most effective for high energy events. The design of these barriers is still under debate and a standardized procedure is not yet available, even though nowadays, following the CE marking procedure, and some National Standards (i.e. UNI11211-4) the current design practice is oriented towards evaluation of the required performances of a barrier in terms of energy absorption capacity and height. On the base of the propagation analyses, the designer selects a suitable commercial product for which it can be checked that block impact energy and passing height are smaller than its performances, considered as the reference value obtained through impacts following the European guidelines (EAD 340059-00-0106, 2018). A partial safety factor approach is generally adopted. Nevertheless, the partial safety factors proposed by the National Standards are fixed values, and thus, neglecting the intrinsic variability and the site specificity of rockfall problems, their adoption inevitably leads to design structures with different failure probabilities (Marchelli *et al*. 2020). Moreover, despite probabilistic trajectory models are adopted, a unique initial scenario in terms of initial volume is generally considered for evaluating the actions.
A time-integrated reliability based design approach has been recently proposed by the Authors (De Biagi *et al*., 2020, Marchelli *et al.* 2020, Marchelli *et al.* 2021a). The reliability calculation accounts for the variability in magnitude of the events, their occurrence probability, and for the intrinsic variability of the actions, with non-fixed probability distributions.
In the following, the mathematical framework of both time-integrated quantitative risk analysis and reliability based design approach are defined, together with their coupling. This last allows to quantify the risk reduction when protective measures are installed.

Time-integrated quantitative risk assessment
Rockfall can be considered a Poisson point process phenomenon: events are independent and have an average frequency of occurrence. From an engineering point of view, the parameter of interest is the frequency of the events reaching the areas where the elements at risk are located, only. The risk calculation should account both for this variability in magnitude, and for the discrete temporal nature of the phenomenon, aspects that have to be considered in mitigation measures design, too. Considering that the exposed area consists of q elements at risk and p rock block volumes that can detach, the risk R has to be computed as (Marchelli *et al*., 2021b):

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

where P_T^l is the temporal probability, which can be associated to the frequency in a given period of time, associated to each possible released volume, $P_S^{l,m}$ is the spatial probability that this block reaches the mth element at risk, and E^m, $V^{l,m}$ and W^m are the exposure, the vulnerability and the value, respectively. As the vulnerability is function not only of the characteristics of the elements at risk but also of the intensity of the phenomenon, for each block volume, and thus for each kinetic energy at the element at risk location, the damages have to be computed.

Reliability based design method for net fences
Considering net fences, the possible failure of these structures can be simplified into a failure mode related to the exceeding height when the block is not intercepted, and one related to the exceeding kinetic energy, when the absorption capacity of the system is smaller than block translational energy. A failure probability is associated to each of them, F_h and F_k, respectively, and, finally, these two are combined into a unique failure probability, named p_f. In a specific period of time τ, this can be computed as (De Biagi *et al*., 2020, Marchelli *et al.* 2020, Marchelli *et al.* 2021a):

$$p_f(\tau) = F_h(\tau) + F_k(\tau) = 2 - e^{-\nu\tau p_{fa,h}} - e^{-\nu\tau p_{fa,k}} \quad (2)$$

being ν the mean expected annual frequency of a rockfall event (of any intensity), and $p_{fa,h}$ and $p_{fa,k}$ the probability of failure for the two failure modes, respectively, considering the occurrence of an event as certain. These probabilities are calculated integrating all the possible block volumes and their occurrence probability (see the referenced papers for details). Provided that distributions of block (i) velocities, (ii) passing heights, (iii) volumes at the impact are provided, together with their probability density functions, a total value of failure probability in the period τ, i.e. $p_f(\tau)$, can be defined for installing a specific product in a specific site.

Coupling the approaches

The introduction of mitigation measures varies the spatial and temporal probability that a block reaches the element at risk. Since $p_f(\tau)$ is calculated with a time-integration for all the possible block volumes, considering τ equal to one year and in the hypothesis that the designed mitigation measures protect all the q elements at risk, Eq. (1) becomes:

$$R_{new} \approx p_f(1\ yr) \sum_{m=1}^{q} (E^m V^{p,m} W^m), \quad (3)$$

assuming that the failure of the measure refers to the largest volume, i.e. p volume, whose temporal probability is in the term $p_f(1\ yr)$. In the case for which only $q_1 < q$ elements at risk are protected, Eq. (1) becomes:

$$R_{new} \approx p_f(1\ yr) \sum_{m=1}^{q} (E^m V^{p,m} W^m) + \sum_{l=1}^{p} \sum_{m=q1+1}^{q} (P_T^l P_S^{l,m} E^m V^{l,m} W^m). \quad (4)$$

Example of application

A sub-vertical rock slope face insists on earth moving vehicles deposit. From a source zone at a height of about 15 m from the deposit, rockfall events different in magnitude (block volume V_b) and frequency can occur. The distribution of the volumes together with their annual release probability have been obtain through monitoring, a catalogue of past events and a survey of blocks in the surroundings. The sampled volumes are distributed according to a Pareto Type I function with threshold volume V_{th} = 0.5 m^3 and whose shape parameter α is equal to 1.6. Due to the verticality of the slope, if detached, a block, in free flight, surely hits the ground, or, in this case, almost a vehicle. Provided that, according to ISO 3449:2005, each vehicle has a maximum impact resistance of 11.6 kJ and has an average value of 20000 €, the risk is calculated according to Eqn. (1). The total risk *R* is of 7300€/year.

To mitigate the risk, protection barriers are planned. Considering the barrier maximum elongation at the impact, the system is installed normal to the slope face at a height of about 10 m from the source zone. Despite free fall represents the most probable type of motion, trajectory analyses are performed, individuating a 95th percentiles of velocity equal to 14 m/s, with a ratio between 99th and 95th percentiles of 1.05, for all V_b. To design the barrier, $P_T^l P_S^{l,m}$ is assumed equal to the mean arrival frequency at the barrier location. A product with energy absorption capacity of 1000 kJ and 5 m high is selected. Its $p_f(1\ yr)$ is computed through Eqn. (2), assuming, due to the nature of both the slope and barrier orientation, $F_h = 0$, i.e. all blocks are intercepted. It reveals $p_f(1\ yr) = 6.1 \cdot 10^{-4}$. The total risk, i.e. Eqn. (4), is R_{new}= 24.4 €/year.

Table 1: Risk calculation without intervention

V_b (m³)	P_T^l (-)	$P_S^{l,m}$ (-)	q (-)	E^m (-)	$V^{l,m}$ (-)	W^m (€)	$R^{l,m}$ (€)
< 0.03	0.5	1	1	1	0.1	20000	1000
$0.03 \leq V_b < 0.1$	0.25	1	1	1	0.3	20000	1500
$0.1 \leq V_b < 0.5$	0.15	1	1	1	0.8	20000	2400
$0.5 \leq V_b < 2$	0.1	1	1	1	1	20000	2000
≥ 2	0.01	1	2	1	1	20000	400

Conclusion

Climate change has a direct impact on mountain areas, and a significant increase of rockfall phenomena has been recorded in the last decades. Thus, an accurate quantification of the risk, accounting for a volume-frequency relationship of all the possible released block volumes, is fundamental for Administrations to manage the risk. Net fences are widely diffused as structural protective measures. The general adopted design method, with a partial safety factor approach, does not account for the volume-frequency relationship and does not allow obtaining a specific failure probability failure. To tackle these issues, a novel time-independent reliability-based design method conceived by the Authors is coupled with time-integrated quantitative risk assessment to quantify the risk reduction in a given time period. The method can thus be used to define the maximum acceptable failure probability of a net fence too.

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