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Towards a procedure to manage safety on construction sites of rockfall protective measures

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ABSTRACT

Construction sites represent ones of the most dangerous workplaces, due to the huge number of hazards related to the performed activities that can cause discomfort, health diseases, and even death to workers. These issues might be even more amplified in construction sites of structures aiming at preventing or protecting against natural hazards. Among these lasts, rockfall represents one of the most unpredictable and dangerous. In these sites, the inherent added hazard is represented by the occurrence of the event against which the protection is required to be installed, i.e. the detachment of a rock block. As in the other situations, workers might be aware of the danger to which they are subjected and all the possible measures to mitigate the risk should be implemented. To address these issues and increase safety of workers, this paper proposes a quantitative risk assessment method to compute the probability of death of workers due to the occurrence of a rockfall event in the considered work duration. In addition, preliminary suggestions to improve safety of workers are delineated.

1. Introduction

Within working activities, the construction industry constitutes one of the most dangerous and most injury-prone due to the huge variety of possible hazards to which workers are exposed (Hassan et al., 2007; Kines et al., 2010). Processes such as heavy manual handling, excavation operations, welding, and work at height might, just to name a few, might involve significant risks to workers (Nakahara and Yokota, 2011; Pinto et al., 2011; Vitharana et al., 2015). The standard ISO 31000:2018 (EN ISO 31000:2018, 2018) on risk management, defines the risk in terms of (i) risk sources, i.e. element that alone or in combination has the potential to give rise to risk, (ii) potential events, i.e. occurrence or change of a particular set of circumstances, (iii) their consequences and (iv) their likelihood. In the framework of working activities, the standard EN ISO 12100:2010 (2010) defines hazard as the potential source of harm, permanently present or unexpected; while harm is the physical injury or damage to health, and risk is the combination of the probability of occurrence of harm and the severity of that harm. In 2013, the International Labour Organization (ILO) estimated that at least 60 000 fatal accidents occur each year on construction sites around the world, i.e. one fatal accident every 10 min (Lingard, 2013). In 2020, a mean value of 10 fatal injuries and 2100 non-fatal injuries per 100 000 workers. Referring to Europe, the Occupational Safety and Health Administration (OSHA) has reported that one in ten construction site workers are injured every year, roughly 150 000 injuries according to the Bureau of Labor Statistics, where falling object hazards represents the leading cause of injury, together with improper use of equipment. Consequences involve not only the loss of working time, but also hospitalization, disability, or even mortality (Dong et al., 1995; Tüchsen et al., 2005), and, consequently, improving workers safety has become an urgent need during the last decades (Spangenberg et al., 2005). The majority of construction companies has thus become sensitive to occupational health and safety (OH&S) problems and have implemented risk management policies, with a proactive, rather than active, approaches (Hecker and Gambatese, 2003). In this framework, following the EN ISO 45001:2018 (2018), several guidelines or also National laws have been developed (Choudhry et al., 2008; Sherratt et al., 2013; Reese, 2018). In addition, training activities on construction site safety have been increasingly implemented, allowing a reduction of avoidable injuries and fatalities and, consequently, enhancing working conditions (Wilkins, 2011). Occupational health and safety policies to prevent work-related injuries and illhealth to workers and to provide safe and healthy workplaces start from the assessment of the potential risks, i.e. evaluating (i) the hazards and (ii) all the possible consequences. Following these, for an effective risk management, preventive procedures and protective measures are adopted and periodically checked. Moreover, risks could be related not

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only to the working activities and to the working environment but also might result from the surrounding environment itself. Focusing on a particular type of construction site, i.e. those in which preventive or protective mitigation measures for natural hazard are installed, the environment itself represents a source of potential risks for workers, and the inherent added hazard is represented by the occurrence of the event for which protection is required.

Among natural hazards, rockfall represents one of the most unpredictable and dangerous (Crosta et al., 2015; Scavia et al., 2020). Due to the increasing number of recorded events, also caused by climate change (Krautblatter et al., 2010; Ravanel and Deline, 2015), the design and the installation of structural protective works, to mitigate the risk on settlements and infrastructures, have become widely common (Vogel et al., 2009; Marchelli et al., 2021). In construction sites related to such structural mitigation measures, the occurrence of a rockfall event itself, e.g. the detachment of a rock block and its impact on machinery, or even workers, represents thus the inherent event, possibly causing malfunctioning/breakage of machinery and injuries/death for workers. As for all the other activities, workers might be aware of the danger to which they are subjected (Wilkins, 2011; Gürcanlı et al., 2015; Zhang et al., 2020), following the new concept for which the human behaviour affects safety of the operations, as well as the surrounding environment and the activities (Sorlini et al., 2022). As these aspects are specific, dynamic, and interactive, the knowledge of all the hazards and, consequently, risks, is fundamental.

Despite the high destructive potential due to the complexity in risk estimation, this potential hazard is often neglected and, consequently, potential damages are not assessed. Trying to fill this gap, the present paper deals with risks connected to the surrounded environment and proposes (i) a quantitative risk assessment method (QRA) specifically related to rockfall hazard in construction sites of rockfall protective measures (Section 3.1), and (ii) suggests some safety policies for risk reduction (Section 3.2). To the knowledge of the Authors no standard or regulation concerning this specific topic exists. Once all the activities performed in such particular construction site are listed (Section 2.1), rockfall hazard is tackled. Neglecting damages on machinery, the considered elements at risk are workers and the possible harm is death, only. The risk is expressed in terms of annual probability of having at least a fatality. As no allowable threshold is provided by legislation, the obtained risk values serve to enterprises or even Authorities in the decision-making process for the OH&S managing plans. The installation of a net fence is taken as an example of application of the proposed procedure (Section 4). Average value of timing for each activity for a 50 m construction site is considered. The application of the proposed QRA method allows to obtain a chart to determine the risk as function of the number of rockfall events in the construction site. This represents a tool for both calculating the risk for a given site and predisposing OH&S policies.

2. Safety in construction site in mountainous areas

Generally speaking, the management of the safety of workers starts from considering the specific work and construction site, in order to list and describe the specific activities, the phases, their organization, their shifts, and the required machinery/scaffolding/provisional works/chemical substances eventually present. The presence of physical agents, such as substances dust, noise, and vibration, possible harsh environment where air is directly exposed to the weather or indoors have to be carefully evaluated. Similarly, the variable nature of the environment, i.e. the adoption of several human resources, also seasonal, and/or constant changes in the construction site configuration have to be carefully tackled. The evaluation of all these aspects allows the assessment of the hazards to which the workers are exposed and their consequences. This information is fundamental to define prevention and protection measures (including individual equipment) to be adopted, and to organize the company's overall OH&S plan with regard to work, machinery and equipment, i.e. define the collective coordination measures (set-up, use of equipment, collective protection infrastructures and services, first aid, etc.). Besides the evaluation of the consequences and their severity, timing in which worker are exposed to hazards in the various activities should be estimated.

As stated above, construction sites related to landslide mitigation measures, additional risks derive from the intrinsic nature of the phenomenon against which intervention is required, i.e. the natural hazardous phenomenon itself. It reveals that, additionally to operations, the environment itself constitutes one of the major sources of potential risks. Focusing on rockfall mitigation measures, to provide a general framework, the possible mitigation measures, both preventive and protective, are reported. They provide the general context within which a specific hazard, i.e. the detachment of a block during construction activities and its arrival on site, consequences and the possibility of avoidance should be assessed.

2.1. Rockfall mitigation measures construction sites

Focusing on rockfall hazard, mitigation measures can be subdivided in preventive and protective (Volkwein et al., 2011; Crosta et al., 2015). Relating to the former, the following types can be individuated: (i) scaling and/or blasting, i.e. the controlled removal of unstable portions creating a stable slope geometry, (ii) rock bolts/dowel, whose aim is to modify the mechanical properties of the joints, consolidating the rock mass knitting it together, (iii) reinforced drapery meshes (Fig. 1, below net fences), i.e. steel wire mesh panels applied on the slope face combined with bolts or anchors, acting on the stability of the block as (ii), (iv) shotcrete, used mainly for the prevention of weathering and spalling of rock slopes, (v) rock anchors, which transfer a tensile load to the slope preventing sliding of blocks, (vi) intervention that modify the hydraulic conditions. Among the protective measures, the following types can be ascribed: (i) rockfall catch ditches, used generally to prevent falling blocks from reaching the road (ii) rockfall barriers, rigid, semi-flexible, and among all, flexible, i.e. net fences, (iii) simple drapery meshes, i.e. steel wire mesh panels suspended from upslope anchors, which drive the detached blocks at the foot of the slope in a controlled manner, (iv) hybrid barriers, i.e. a system combining net fences with simple drapery, (v) rockfall tunnel, in which a reinforced concrete structure is covered by a cushion layer of granular material, (vi) embankments, i.e. any structure in elevation of at least 2 m, mostly made of granular material with the aim of intercepting falling blocks. Among all these protective measures, net fences constitute one of the most adopted technologies (Peila and Ronco, 2009; Marchelli et al., 2020). They are essentially made of a wire net, intercepting and stopping the falling blocks through deformation, sustained by metallic posts and connecting components, which transfer the impact loads to the foundations. Net fences can be considered as a sequence of functional modules, generally with a longitudinal length of 8–10 m, of an intercepting structure, i.e. the net, a support structure, i.e. posts, and connection components (Figs. 1 and 2). Focusing on protective works, construction sites can be very complex from the safety management point of view as they can be located in the rockfall source area (i.e. drapery meshes), in the transit zone (e.g. drapery meshes, net fences, hybrid barriers), and in the depositional zone (e.g. net fences, embankments, tunnels).

Taking net fences construction site as an example (Fig. 2), to correctly evaluate the possible hazards, the consequences, and the ways to avoid them, operations should be firstly listed together with used machinery, tools and substances, considering number of workers, timing and interference. With reference to a protective work construction site, the activities directly on the rock face, where rock blocks detachment can occur, can be neglected. This assumption does not hold for drapery meshes or preventive measures. Nevertheless, it is worth mentioning that in some cases, removal of unstable blocks, reclamation and vegetation clearing are often performed before the preparation of the net fence construction site. The main sequential stages are:

Fig. 1. Net fence and drapery mesh construction sites (Lago Maggiore, Italy).

1. creation of the construction site track for the length necessary to install the whole of the rockfall barrier, also considering the lateral anchorages at the beginning and end of the line;
2. topographical tracking and realization of anchors for lateral, upstream, longitudinal support ropes, as well of the foundation of the barrier posts;
3. preparation of the parts for the assembly, i.e. unloading supplier's truck and arranging the beams, panels and ropes, in a safe area or directly where net fence is located;
4. assembly of posts and nets;
5. tensioning of ropes, sewing operations, positioning of the secondary fine mesh, installation of connecting devices, and final cleaning.

Referring to point 4., it is frequent the case in which nets and uprights are pre-assembled in the manufacturer's factory and moved by helicopter to the place of installation. During these operations, risks derived (i) by the interference between the construction site/operations and the environment, (ii) inside the construction site during activities, and (iii) by the surrounding environment itself should be considered and evaluated. Starting from the first aspect, assuming that helicopter is used for the movement of posts and nets, interference with power lines, vegetation, and buildings/works, together with the possible lifting of dust, raise of noise, and falling of material should be assessed. Falling from material can be caused also by vegetation clearing operations. In relation to the second aspect, machinery that are generally used are: truck, helicopter, carving machine, air compressor, generator, water pump, drilling machine on support, motorized brushcutter, chainsaw, hand tools, hydraulic hand jack, iron levers, ropes. The listed material and equipment handling and the installation procedures expose workers to possible impacts, blows, compression, shearing, crushing, cuts, abrasions, electric shocks, blows, falls from heights and noise. The possible use of special machinery involves exposure to risks of toxic gas inhalation, whole-body vibration, noise, or damage from hot oils. In addition, as these operations are performed in often complex mountain environments, also weather conditions, that can change rapidly (wind, rain, or snow), should be examined (Alfaro Degan et al., 2020, 2022; Forteza et al., 2022). It is worth noting that some of the possible risks can arise also during maintenance operations. Finally, the third aspect is connected to the occurrence of the hazardous phenomenon for which net fences are required, i.e. rockfall event, generally unpredictable and involving high kinetic energy. Protective measures are generally designed to intercept and stop blocks up to a given volume with a given kinetic energy. The magnitude of the event relates to an exceptional scenario, e.g. with a return period of about 100–200 years, according to the administrator or designer judgment. Nevertheless, smaller rockfall events with a lower return period, i.e. with a higher frequency, can occur. The interference between these blocks and the activities should be properly tackled during risk assessment for machinery and workers. The preventive removal of unstable small blocks before net fence installation certainly lowers this hazard, but, unavoidably, involves additional risks for the activities directly on the rock face. To the knowledge of the Authors no standard or regulation concerning specifically this issue, but risk in working environment is addressed in a general way. As an example, the Italian regulation on OH&S issues is briefly reported.

2.1.1. Regulations and standards: the case of Italy

In Italy, D.lgs. 9/04/2008, n. 81 (2008) represents the national law regarding OS&H, including all the types of work, and therefore mandatory also for those in the mountain environment. The law defines the key elements that constitute a good basis for safety in an organization, including all safety figures that have a relevant role in the organizational structure. It reports the requirements for ensuring the safety of workers in any working environment, such as hospitals, factories, offices, and construction sites. The law is divided into 13 sections, each covering a specific safety issue. As reported in Art. 2, this law emphasizes that the employer, defined as the subject who holds the employment relationship with the worker, is responsible for the organization itself (or the production unit) and for performing all necessary safety measures to prevent accidents and injuries to workers. The first of the 13 sections defines and discusses hazards, risks and prevention/protection measures. It should be emphasized that the risk assessment process is based on a dynamic development that requires the integration of safety measures into all aspects of an organization's activities. Risk assessment procedures in the context of construction sites are dealt specifically in the fourth section, in which general or even specific rules, i.e. those related to the use of scaffolding or logistic organization of the construction site, are listed. Possible risks are treated, highlighting that they might be due also to the interference among the activities, as workers from many companies and a variety of trades (e.g., roofers, carpenters, electricians, plumbers, painters, etc.), performing different activities at the same time, are involved. Preventive and protective measures for work at height are reported also. Nevertheless, no specific rules are defined concerning construction site exposed to natural hazards such as rockfall, and thus the only reference document is D.lgs. 9/04/2008, n. 81 (2008).

3. A methodology to manage safety on construction sites for protection works

Referring to natural hazard, the United Nations Office for Disaster Risk Reduction (UNDRR) defines disaster risk as the potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time. It is probabilistically determined as a function of hazard, exposure, vulnerability and capacity (UNDRR, 2016). This definition is in line with what reported by Fell et al. (2005, 2008), proposing guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Exposure, vulnerability and capacity (or value) refer to the elements at risk: exposure represents the probability that the elements are exposed to potential loss, while vulnerability is the degree of loss, both when a phenomenon of given intensity spatial and temporal probability occurs.

Focusing on the specific risk derived by the detachment and fall of a rock block on the construction site, defined as possible source of inherent environmental risk related to the particular environment in which the site is, a quantitative assessment method to evaluate the risk for workers on construction sites of rockfall protective measures is herein delineated.

Then, several suggestions related to the measures for mitigating this risk are proposed.

Fig. 2. Rockfall net fences construction sites.
Source: Courtesy of Geobrugg Italia S.r.l.

3.1. Quantitative risk assessment

In agreement with natural hazard definitions (Fell, 1994; Corominas et al., 2014), rockfall hazard refers to the probability of occurrence of an event of a given volume and kinetic energy over a predefined period of time and within a given area, i.e., in the case herein analysed, during operations in the construction site. In other words, as for landslides, floods, earthquakes or volcanic eruptions, assessing rockfall hazard means evaluating the location, magnitude and probability of occurrence in a given time period, and then their propagation (Dussauge-Peisser et al., 2002). As stated in Section 2.1, in fact, similarly to the other natural hazards, rockfall events can repeat several times in the same area, involving blocks whose volume can be differ each time (Dussauge et al., 2003). The quantification of the risk involves also the characterization of the elements at risk and, thus, the evaluation of potential impact on vulnerable infrastructures, structures or people. One of the common ways to input the kinetic energies impacting on the elements at risk is to establish a link between the magnitude of the potential events and the corresponding return period (De Biagi et al., 2017; De Biagi, 2017; Moos et al., 2022). Volume–frequency laws can be defined on the source area, i.e. through photogrammetry techniques together with geological surveys of the rock cliff and inventory data (Sarro et al., 2018; Farmakis et al., 2020; Fei et al., 2023), and through propagation analyses (Bourrier and Hungr, 2011; Dorren et al., 2011; Li and Lan, 2015) the trajectories, heights and energies of the released blocks are quantified in a probabilistic framework. As repeatable landslide phenomena, rockfall is generally treated as a Poisson point process phenomenon (McClung, 1999), in which the events are independent, with an average frequency of occurrence according to their magnitude. Generally rockfall QRA methods adopted for infrastructures or mountain villages usually provide a risk quantification in probabilistic terms. This last is related to the average consequences in terms of societal risk, often in terms of a relationship between the frequency of the events and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards (Jonkman et al., 2003; Tesfamariam and Goda, 2013). The societal risk gives a number for a whole area, no matter precisely where the harm occurs within that area, being function of the frequency of each hazard, the total number of people affected and their exposure (Muhlbauer, 2004). In other words, the societal risk of fatality due to rockfalls on an annual basis represents, in some extents, the average number of people killed by rockfall occurrence each year in the considered area. In workplace context, instead, the individual risk is usually defined, i.e. the likelihood of an individual (worker) in a given location (workplace) being injured/dying by the occurrence of the hazardous event. Individual risk computes thus the highest probability that a worker has to suffer for an injury or death as a result of the event. So, while the individual risk is a point-wise risk measure, societal risk is inherently a spatial aggregate risk measure (Broccardo et al., 2017). As the societal risk, expressed as aggregate weighted risk, can be calculated by multiplying the number of elements at risk (e.g. workers) inside a certain area (e.g. the construction site) with their individual risk (IR) level (Piers, 1998), assuming an equal IR for each worker, the individual risk can be estimated by dividing the societal risk by the total number of workers.

Applying the above-mentioned concepts and definitions to rockfall events on construction sites, the risk assessment must account both for the variability in magnitude, and for the discrete temporal nature of the phenomenon. Assuming the exposed area consisting of q elements at risk, e.g. workers (and machinery), and p rock block volume classes that can detach, the societal risk R_s can be evaluated in a probabilistic way as proposed by several authors (Corominas et al., 2005; Moos et al., 2018; Farvacque et al., 2019; Kanno et al., 2023):

$$R_s = \sum_{l=1}^{p} \sum_{m=1}^{q} \left(P^l_{(T:B)} P^l_{(S:B)} E^m V^{l,m} W^m \right), \tag{1}$$

where $P^l_{(T:B)}$ is the temporal probability (subscript $_T$), i.e. the probability of occurrence, that a block (subscript $_B$) of magnitude l detaches and $P^l_{(S:B)}$ the spatial probability (subscript S) that the block reaches the mth element at risk; E^m, $V^{l,m}$, W^m are the exposure, i.e. the probability that a given element is at the impact location where the rock block detaches, the vulnerability, i.e. the degree of loss (injury/death) due to a block impacting on the element, and the value of the element itself, eventually in monetary terms, respectively. The temporal probability $P^l_{(T:B)}$ derives from the volume–frequency law, while the spatial probability $P^l_{(S:B)}$ results from propagation analyses for each volume class. In the present case, the considered elements at risk are workers, only. In this context, due to the involved high velocities (up to 30 m/s) and, thus, the kinetic energies of the possible impacting blocks, it is assumed that, if impacted, a worker dies. This assumption holds under the hypothesis that the personal protection equipment for personnel, i.e. helmet, has an impact resistance against a falling object of about 50 J, in accordance with E.N. 397:2012 (2012) and Regulation (EU) 2016/425 (2016), i.e. generally much lower than the kinetic energy involved in rockfall events. Moreover, in the present paper the value W^m is neglected (or assumed equal to 1), avoiding to express the value of human life in monetary terms. A relative risk is thus calculated. The calculation can provide a quantification of the societal risk in terms of annual probability of having at least one damage (fatality), approximated to the number of damages per year, as often required by Authorities. Not to burden with the notation R_s continues to be used. Following these considerations, Eq. (1) becomes:

$$R_s = \sum_{l=1}^{p} \left(P^l_{(T:B)} P^l_{(S:B)} \right) \sum_{m=1}^{n_w} E^m, \tag{2}$$

being n_w the total number of workers. Assuming that workers are equally exposed, with a value $E^m = E$ the individual risk R_i is thus equal to:

$$R_i = E \sum_{l=1}^{p} \left(P^l_{(T:B)} P^l_{(S:B)} \right) = \frac{R_s}{n_w}. \tag{3}$$

It should be noted that although several techniques for the estimation of $P^l_{(T:B)}$ for each volume class exist (Hungr et al., 1999; Dussauge-Peisser et al., 2002; Graber and Santi, 2022), the obtained values may be sometimes affected by inaccuracy due to lack of data (De Biagi, 2017; Moos et al., 2022). When photogrammetric and/or geological survey data lack accuracy and when information on past events is related only to those phenomena which have affected sensitive structures or infrastructures, Marchelli (2020) proposed a method to evaluate $P^l_{(T:B)}$ starting from the knowledge of only the blocks reaching the urbanized area (target), whose total number is defined as $N_{B,r}$, and from the results of the trajectory analyses. As protective measures are installed in between the source areas and the vulnerable buildings or infrastructure, the number of events that can impacts on the construction site, $N_{B,c}$, can be approximately estimated as:

$$N_{B,c} = \frac{\sum_{l=1}^{p} P^l_{(S:B)}}{\sum_{l=1}^{p} P^l_{(S:B)r}} N_{B,r} \tag{4}$$

being $P^l_{(S:B)r}$ the spatial probability that a block of volume class l arrives on the road. Thus, in the hypothesis of a small number of events, the term $\sum_{l=1}^{p} \left(P^l_{(T:B)} P^l_{(S:B)} \right)$ can be approximated to $N_{B,c}$. It should be noted that, in principle, along its entire length ℓ_c, the construction site be reached by the blocks with different probabilities. For long construction sites, in the hypothesis of subdividing the total length in k sections (of length ℓ_k) with equal $P^l_{(S:B)}$, for each section, the number of arriving blocks N_{B,c_k} can be evaluated as:

$$N_{B,c_k} = \frac{P^l_{(S:B)k} \ell_k}{\sum_k P^l_{(S:B)k} \ell_k} N_{B,c}. \tag{5}$$

The exposure of a worker E is related to the duration of his/her stay in the hazardous area in terms of working hours n_h in the site and thus to the spatial $P_{(S:W)}$ and temporal $P_{(T:W)}$ probability that a worker is precisely in the location and at the time of block arrival and, hence, he/she is hit. Considering workers permanently exposed to the hazard during the work, $P_{(T:W)}$ is equal to the ratio between the number of working hours n_h and the reference time period in which risk should be evaluated expressed in hours, e.g. for one year equal to 8760 h. The spatial probability $P_{(S:W)}$ is provided by the ratio between a person size l_w, i.e. 60 cm, and the construction site length ℓ_c (Marchelli, 2020; Marchelli et al., 2021). Consequently,

$$E = P_{(T:W)} P_{(S:W)} = \frac{n_h l_w}{8760 \ell_c}. \tag{6}$$

Finally, R_c can thus be computed as:

$$R_c = n_w \sum_k \left(1 - (1 - E)^{N_{B,c,k}} \right). \tag{7}$$

3.2. Proposed measure for safety management

Following what explained in Section 3.1, safety management for workers starts by computing the individual (or the societal) risk in the specific construction site. Considering the actual mandatory regulations, a predefined acceptable or tolerable threshold for the risk has not defined yet. Acceptable risk refers to the risk value that the general public is inclined to accept without regard to its management for life and work purposes. Tolerable risk refers to the value that the general public is inclined to live with in order to safeguard certain net benefits, assuming that the particular risk is being properly contained (Sim et al., 2022). For societal risk, the Italian Standard UNI 11211-2 (2007) suggests to consider a value in between 10^{-6} and 10^{-5} as reasonably acceptable in case of rockfall protected structures or infrastructures. Moreover, a higher threshold, e.g. equal to 10^{-4}, is mentioned in those situation in which people are subjected to a risk, of any origin, by a volunteering basis, e.g. when they drive or while working. Generally speaking, Jonkman et al. (2003) reports that in the Netherlands, referring to the individual risk, the acceptable threshold is 10^{-6} for workers in factory, while 10^{-3} for mountaineering activities, varying thus the threshold value according to the degree to which participation in the activity is voluntary and with the perceived benefit. Similarly, Bohnenblust (1998) studying the safety of the railway system in Germany, reported the same thresholds. The UK's health and safety executive document on the tolerability of risks in nuclear stations (Health and Executive, 1992) suggests values of 10^{-3} for workers and 10^{-5} for the members of the public, as a boundary between the tolerable and the acceptable regions.

Once defined an acceptability threshold, mitigation measures to reduce the risk should be implemented whenever the risk overcomes this threshold. As for the threshold definition, predefined procedures to reduce the risk in rockfall construction site environment has not codified yet. In the present study some useful suggestions are proposed, considering that the suitability of each of them should be verified case by case. All the presented methods relate with the concept of monitoring, and, considering the abruptness of rockfall phenomena, can be more or less effective depending on the morphological characteristics of the slope and, undoubtedly, the proximity of the construction site to the rockfall source zone. The majority of the solutions herein listed has sometimes been adopted on different sites but without a specific standardization. Monitoring in the source zone can be achieved in different ways herein discussed:

- active monitoring thanks to displacement transducers installed on the major joints or discontinuities of the rock, combined with a data acquisition, processing and transmission system, properly powered;
- periodic inspection by experienced personnel, with a fixed time step or after intense rainfall or abnormal weather conditions, e.g. sudden changes in temperature;
- passive permanent monitoring of the rock face conditions thanks to georadar, with sub-mm displacement accuracy, combined with machine learning techniques to individuate changes in some pre-defined characteristics, e.g. aperture of the discontinuities;
- passive permanent monitoring with radar which provides an automatic real-time detection of rockfall;
- passive permanent monitoring for real-time detection of rockfall provided by one worker. It is necessary point out that workers must have a specific training accordingly to EN ISO 45001:2018 (2018). In this case the "sentinel" worker should be trained regarding to all the specific events that can generate rockfalls.

The proposed solutions should be combined with an alert system, and thus the identification of warning and alert threshold, as well as the definition of effective actions for each threshold, e.g. evacuation, is required. Neglecting the real-time rockfall detection solutions, for which the most effective solution is to provide some audible alarm as soon as a block detachment or movement is noticed, for rock face conditions monitoring system can represent a crucial issue. The definition of a displacement threshold should be calibrated according to the daily and seasonal temperature variations and this requires time that cannot be always affordable either from an economic point of view or considering the safety of the elements at risk for which protective measures have been considered necessary. Indeed, radar solutions, despite their capability to operate permanently in any weather and at night, need to be installed in such a way to be capable to see the whole rock face. A last aspect should be the effectiveness of the alert system itself: in case in which the construction site is close to the source zone, the time needed to escape once received the alarm is not sufficient. All these points should be considered in the management and design of the safety procedure to adopt. In some cases, old rockfall mitigation measures, previously installed and no more completely effective, can be present along the slope. These works can be equipped with impact sensors: when a block impacts against these works, they activate and send the signal. In addition, in some cases they can be used as fuse elements and even not effective to completely protect the element at risk they can reduce the risk during installation operations. In absence of other works, the same system to recognize and signal the impacts can be easily achieved by installing a simple construction site-protective net, with the only aim to allow the sensor to detect the impact. The proposed solutions are examples; a deep analysis of the specificity of each site should be performed.

4. Application

A net fence construction site is considered as an example. Neglecting specific risks related to the interference between the construction site/operations and the environment, and risks inherent in the operations, risks to worker related to a rockfall event on the construction site are analysed. As expressed in Section 3.1, the risk, can be expressed in terms of annual probability of a single worker to have a fatality (individual) or in terms of societal risk. A relatively standard situation is considered, i.e. where morphology of the slope does not require the installation of special devices or where machinery can be easily delivered to site. A construction site for net fences 50 m long, measured parallel to the net fence, is considered. Three workers have been considered as minimum requirement. In relation to the operations listed in Section 2.1, the input data related to number of hours are:

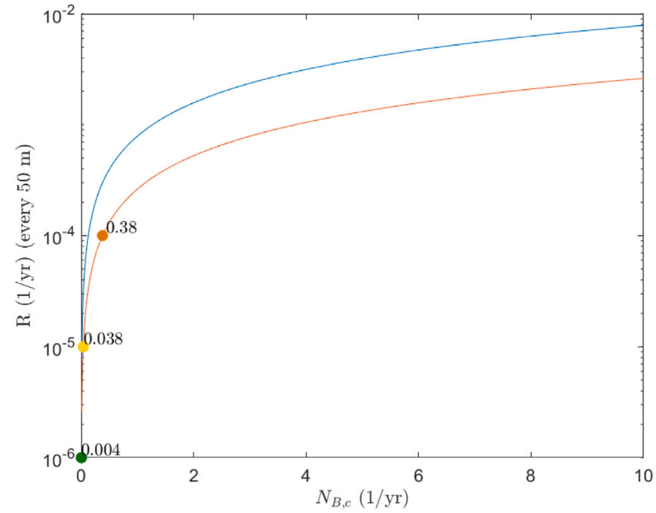

Fig. 3. Annual risk due to rockfall hazard in a construction site for a 50 m long protective measure. In blue the societal risk, in orange the individual risk. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- building of the construction site track: 5 working days;
- topographical tracking and realization of anchors, considering drilling and grouting operations without any specific problem: 11 working days;
- preparation of the material for assembly: 2 working days;
- assembly of posts and nets: 3 working days;
- tensioning of ropes, sewing operations, positioning of the secondary fine mesh, installation of connecting devices, and cleaning: 3 working days.

A total time of 24 working days, i.e. 192 h for each worker have been considered. The hypothesis of $j = 1$, i.e. the blocks potentially insisting on the construction site have the same probability to detach, can be generally assumed for blocks derived from the same source zone. Moreover, trajectory analyses should always be performed to correctly design net fences, and, thus, they can be used to determine $N_{B,c}$ from $N_{B,r}$. Following the calculations expressed in Section 3.1, the proposed method allows creating a chart to determine the risk as function of the annual number of blocks arriving on the construction site. The annual basis has been selected as the acceptability threshold is generally expressed with this reference period. Fig. 3 reports a plot of the risk as function of $N_{B,c}$. It should be noted that the obtained risk values are related to rockfall hazards, only. Assuming thus a similar working setup (number of workers and working hours), for each net fence construction site, knowing from site-dependent calculations $N_{B,c}$ (Section 3.1), the chart of Fig. 3 allows determining the annual risk for a 50 m-long site. Thanks to the properties of probabilities related to independent events, the risk for longer net fences, and thus site, can be obtained by summation, i.e. for 100 m the risk is obtained summing the risk for two 50 m-long sites. For particular working setups, the risk could instead be quantified following the procedure of Section 3.1. Once a threshold level of acceptability is defined, if the obtained risk is greater than the acceptable one, some powerful countermeasure to lower the risk might be adopted, as those presented in Section 3.2.

5. Conclusions

Among workplaces, construction sites represent ones of the most dangerous for workers, considering both working activities and the environment itself. In construction sites for structures aiming at preventing or protecting from a natural hazard, risks are even more higher, as in these sites, the inherent added hazard is represented by the occurrence of the event for which protection is being installed. Among natural hazards, rockfall represents one of the most unpredictable and dangerous. In rockfall mitigation measures construction sites, the occurrence of a rockfall, i.e. the detachment of a rock block that can impact on workers and machinery, represent the inherent risk. To minimize the risk, employers and workers might be aware of the danger to which they are subjected and all the possible measures to mitigate it should be implemented. To address these issues and increase safety of workers, this paper proposes a quantitative risk assessment method to compute the probability of death of workers due to the occurrence of a rockfall event during the construction period. A construction site for net fences is taken as an example for applying the proposed procedure, considering average value of timing for each activity for a 50 m long protection measure. A graph to determine the risk as function of the number of events, i.e. blocks arrival, in the construction site is obtained. The graph can be used in standard net fence working setup to evaluate the annual risk, knowing the occurred number of events per year. Assuming the obtained risk value greater than a predefined acceptability threshold, suggestions on possible mitigation measures for workers are herein delineated, concerning prevention, protection and training. The adoption of such measures depends on the characteristics of the construction site itself. Nevertheless, the figure of a person responsible for a constant monitoring activity of the rock slope face is in line with what prescribed by the Italian regulation. Future works can deal with machinery risk assessment or can be devoted to design new tools for workers protection. In addition, the method can be used for other passive mitigation measures, as rockfall embankments.

CRediT authorship contribution statement

Maddalena Marchelli: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Gianluca Coltrinari:** Writing – original draft, Conceptualization. **Guido Alfaro Degan:** Supervision, Conceptualization. **Daniele Peila:** Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

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