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FAILURE PROBABILITY OF ROCKFALL NET FENCES SUBJECTED TO AGEING: A RELIABILITY-BASED APPROACH FOR RISK REDUCTION

Valerio De Biagi

Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Italy.
E-mail: valerio.debiagi@polito.it

Maddalena Marchelli

Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Italy.
E-mail: maddalena.marchelli@polito.it

Francesco Pimpinella

Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Italy.
E-mail: francesco.pimpinella@polito.it

Net fences, or rockfall flexible barriers, are rockfall risk mitigation structures that have an inherent failure probability. Analysing the variability of the phenomenon and the uncertainties associated to the prediction of the trajectories of the potentially falling blocks, the Authors have found that the adoption of non site-specific partial safety factors, as suggested in Italian and Austrian rules and the European Guidelines, would lead to a wide range of failure probabilities. Hence, they have introduced a new approach tailored for any slope that implements a time-integrated reliability-based analysis. All the previously discussed analyses have been performed on new structures, considering a Dirac-δ distribution for the capacity of the barrier. The present contribution deals with the introduction of ageing phenomena (e.g. corrosion of components, untightening of connections, etc) or the activation of the energy dissipating devices into the evaluation of the failure probability of the barrier. Numerical and analytical modelling and recent tests on artificially corroded barrier components have shown an overall reduction of energy dissipation capacity. Based on the assessment of the current state of a net fence, an appropriate distribution that accounts for the reduction of the capacity and the uncertainties in the evaluation of the ageing parameters is introduced, and the effects on the failure probability of the system are quantified. An example of application is included, showing how risk reduction can be efficiently achieved by considering the effective failure probability of the net fences.

Keywords: Rockfall, net fence, failure probability, reliability-based analysis, ageing.

1. Introduction

Rockfall is a high energy natural hazard that can pose a serious threat to inhabited areas and infrastructure in mountainous areas. Rockfall net fences (or barriers) represent one of the most widely used passive structural systems to reduce the risk of rockfall. Such devices, installed along the slope where the natural event is expected, are aimed to intercept the blocks and stop their movement thanks to the dissipation of energy through permanent deformation of the structural system, essentially made by a metallic net supported by metallic posts and connected to the foundations through ropes. Although they have been widely adopted, the design of these systems has not yet been fully codified. Some European rules are based on a partial safety factor format, suggesting checking whether the factored capacity is greater than the increased action, for both energy and height design. In details, taking the UNI 11211-4 (UNI 2018) as an example, the actions are evaluated from the characteristic values of the mass, velocity, trajectory height of the design block, while the resistances are defined in terms of barrier height and energy absorption capacity. The size of the block, hence its mass, is obtained from a survey along the slope and its value corresponds to the 95th percentile of the surveyed blocks. The propagation analysis provides the distributions of velocity and height at barrier location and the characteristic values are its 95th percentiles. Last, the performances of the barrier are assessed through standardized impact tests (EAD 340059-00-0106:2018), for which the resisting energy at the MEL (maximum energy level) test represents the characteristic value of the capacity of the barrier. Although such an approach provides a simple method for designing the protection structure, it completely ignores the failure probability of the system itself.

1.1. *Basics on time-integrated reliability calculations for rockfall barriers*

As any other structure subject to hazards, the system can fail and the knowledge of the temporal, i.e. annual, failure probability is of outmost importance in assessing the risk in engineered slopes. The Authors have proposed a mathematical framework for calculating the system's probability of failure based on reliability-based considerations (De Biagi et al. 2020; Marchelli et al. 2020, 2021). Unlike other approaches available in the literature, their method allows considering all potential block volumes that can reach the mitigation measure, taking into account the fact that small blocks are more frequent than large ones. In the simplified framework, the failure probability F_k associated to the excessive energy, i.e., block kinetic energy is larger than barrier capacity, in t years is:

$$F_k = 1 - \exp\left[-\lambda t \int_0^{\infty} p_f(\mu) f_{m_k}(\mu) d\mu\right] \quad (1)$$

where λ is the average frequency of rockfall events along the slope and $f_{mk}(\mu)$ is the probability that the fallen block has mass equal to μ. The term $p_f(\mu)$ is the failure probability if the falling block has average mass equal to μ and it is the probability that the state function $K = E_b - 1/2mv^2$, being E_b the nominal capacity of the barrier, has negative values. The mass of the block m is obtained from a normal distribution centered in μ. Under the lumped mass assumption, the velocity v is defined from a normal distribution that well fits the right tail of the distribution of the velocity at the barrier location obtained as output of the trajectory analysis. The distribution of the barrier energy capacity E_b has been considered as a Dirac-δ at the MEL value provided by the producer. A similar analysis can be performed considering the failure due to excessive height. The complete description of the mathematics behind the formulae is reported in De Biagi et al. (2020) and Marchelli et al. (2020, 2021). The procedure provides the design values of the variables and, by consequence, the value of the partial safety factor to be applied to the characteristic values.

One of the major outcomes of the framework is that the problem is site-specific as, despite being fixed in the national standards above mentioned, the calculated partial safety factors significantly differ from site to site. In other words, keeping the factors fixed would imply a different failure probability site- by-site. For design purposes, Marchelli et al. (2021) have performed a calibration of the partial safety factors on a wide range of masses, velocities and trajectory heights. The time-integrated formulation offers two potentials: it provides the design characteristics of the protection system for a given probability of failure or, given a network fence, allows its probability of failure to be quantified.

One of the major issues of the described approach lies in the mathematical description of the capacity the barrier, so far considered with a Dirac-δ distribution, as mentioned. For newly installed barriers, this assumption does not take into account the real variability of the response of the system according to the impact position, resulting in an overcapacity or in a possible reduction due to an installation that deviates from the tested condition. For existing barriers, the effects of ageing or other potential defects that may originate on the main components might reduce significantly the performances of the barriers during time. The present paper introduces into the reliability-based calculations the effects of ageing to assess the variation on the failure probability of the system.

2. Ageing of rockfall barriers

During the working life, the structures are subjected to several threats: first, rockfall events can occur, with the possibility that the energy dissipating devices (also called brakes or dissipators) are activated, and/or the net is permanently deformed. In addition, environmental conditions (water, chemicals from the ground, air pollution) can reduce the thickness of the zinc coating on steel components and activate corrosion mechanisms (De La Fuente et al. 2007). Freezing/thaw cycles act on the bolted connections by reducing the slip resistance, or the vegetation can grow on the net, limiting its deformability. In addition, localised corrosions due to eddy currents can be observed if the protective structure is closed to power lines. Although EAD 340059-00-0106 states that the expected working life of rockfall barriers is 25 years (EOTA 2018), the protective measure currently installed are usually older, with the possibility of having severe damage conditions (Hoffmann et al. 2023). Marchelli et al. (2022) proposed a multi-criteria procedure to assess the ageing condition on a rockfall flexible barrier, providing a qualitative evaluation of the potential effects on the efficiency of the measure. Govoni and Strada (2015) addressed a similar problem on rigid barriers. As a result of ageing, the capacity of the barrier is reduced. To the knowledge of the Authors, no specific procedures to quantify the energy absorption capacity of a rockfall system that underwent damage are available. In the following, we propose a simple methodology to quantify the distribution of the barrier energy capacity E_b, to be included in the reliability calculations described in the previous section.

3. Modelling damaged barriers

An integrated analytical model of a standard rockfall system made of intercepting net, ropes and dissipators was built with the specific purpose to study how the force-punching curve of a barrier is affected by the variability of the single components (Pimpinella et al. 2024). A ring-net barrier with dissipators is considered in this study. Briefly, the system consists in a 10 m wide, 4.5 m tall barrier module made of a four contact points wire ring net R12/3/300 (windings/wire diameter/ring diameter, in mm). Top and bottom 22 mm diameter longitudinal ropes are connected to the posts' ends and, then, to equivalent energy dissipators which activate at 120 kN and have a maximum stroke (elongation of the equivalent dissipator) of 2.20 m. Starting from the existing model for a ring net by Guo et al. (2022), our model of the whole system includes ropes and dissipators behaviours. Figure 1 details the components of the model: the net N is composed of longitudinal and transversal equivalent fibres (n_i) that are linked to the transversal and longitudinal ropes (r), respectively. The ropes are equipped with dissipators (d) and connected to the foundations (*f*). When a force F is applied to the centre of the net (i.e., in the grey panel), the fibres transfer the force to the ropes and then to the dissipators/foundations. The force causes displacements: elongations in the fibres, deflection and elongation in the rope. If the force in each rope exceeds the activation force of the dissipator a stroke is expected and the rope slides on the roller at the end each post (p). The total displacement of the point of application of the force is η. An incremental pushdown analysis is performed on the system and the displacement corresponding to each force level is determined. It is assumed that the energy absorbed by the system is the integral of the force-displacement curve.

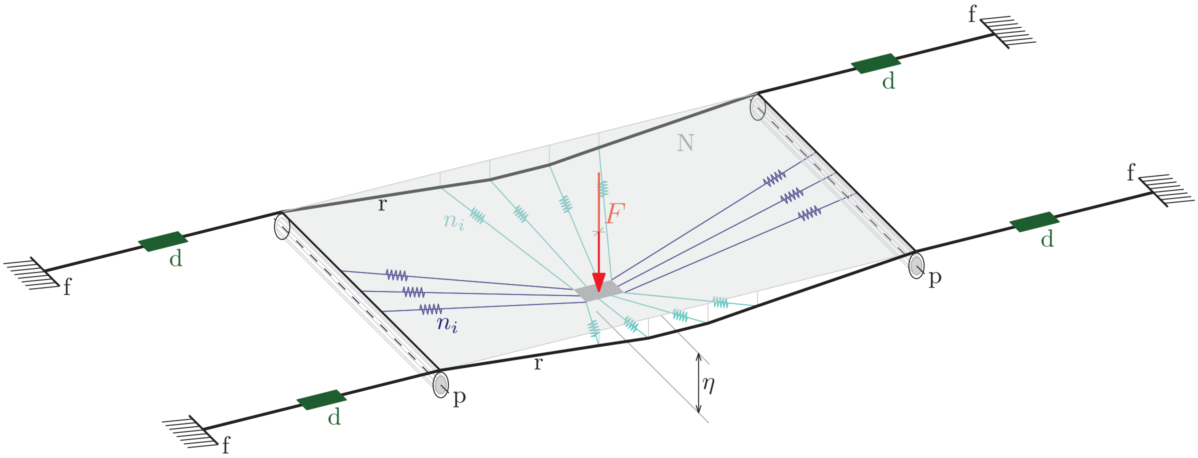

Fig. 1. Schematics of the proposed analytical model of the whole barrier. The reader should refer to the text for the symbols.

A Monte-Carlo analysis of the energy absorption capacity of the undamaged system was performed by varying the width of the module, considering the uncertainty in the correct rope diameter and ring-net performance. At this stage, a centred impact is considered, only. The 2000 normal distributed samples were extracted varying the parameters reported in the second column of Table 1. For each case, the force- punching curve was determined and the dissipating capacity of the system was assumed as the total work performed by the force. The set of normalized capacities results as the ratio between the computed capacities and a reference value resulting from a deterministic study on a barrier with no variability in the input parameters. Figure 2a reports the histogram of the obtained normalized capacities for an undamaged case. The blue curve refers to a normal distribution having mean equal to 0.974 and standard deviation of 0.046. The same analysis was repeated on a damaged set of parameters. The damage was applied to the rope diameter, which was reduced between 0 and 1.5 mm, and to yielding and ultimate forces of the ring-net, as reported in the third column of Table 1. The applied damage was included by reducing the values of a quantify randomly extracted from a uniform distribution ($\mathcal{U}$ in Table 1), as often is observed in real systems that experience localized corrosion (Melchers 2018). The resulting normalized dataset is reported in Figure 2b, with the red curve referring to a normal distribution having mean equal to 0.944 and standard deviation of 0.048. On average, the reduction is about 3%, while the standard deviation remains equal. The obtained information turns to be the capacity of the barrier to be introduced in the reliability calculations according to Eq.(1).

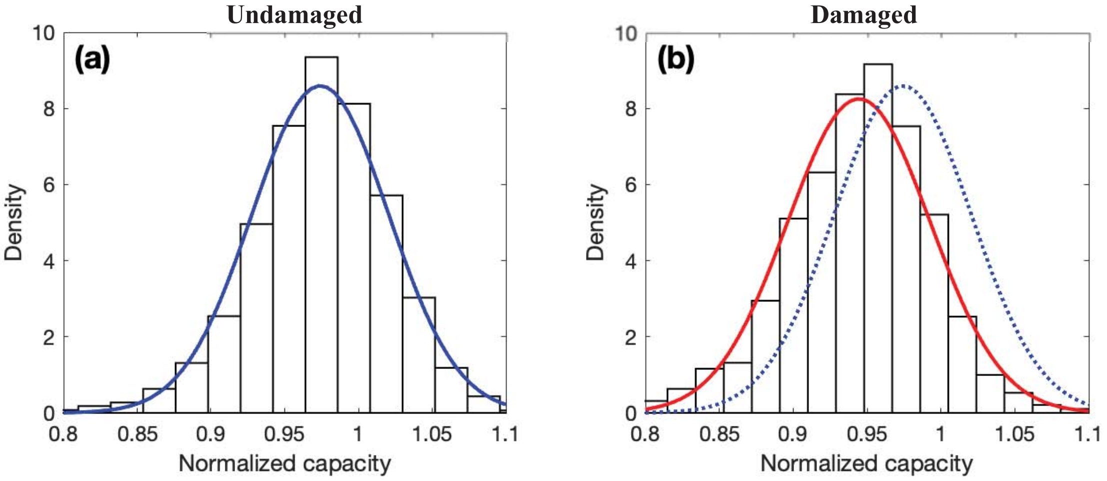

Fig. 2. Normalized capacities of an undamaged system (a) and of a system with reduced rope and ring-net performances (b). The dotted curve in (b) is the interpolating curve of the undamaged system (a).

Table 1. Mean and standard deviation of the input parameters for the Monte-Carlo analysis.

Parameter	Undamaged	Rope and ring-net
Module width [m]	10.0± 0.3	10.0± 0.3
Rope diameter [mm]	22.0± 0.3	22.0± 0.3 – $\mathcal{U}(0;1.5)$
Rope Young's modulus [GPa]	60.0± 5.0	60.0± 5.0
3-rings yielding force [kN]	9.0± 0.5	9.0± 0.5 – $\mathcal{U}(0;1.0)$
3-rings ultimate force [kN]	110.0± 3.0	110.0± 3.0 – $\mathcal{U}(0;5.0)$

4. Conclusions

This conference paper illustrates the preliminary work on the evaluation of the effects of ageing and damages on the capacity performance of a rockfall barrier. To achieve such objective, an integrated model that simulates the behaviour of the intercepting net, ropes and dissipators was introduced. A Monte-Carlo analysis accounting for the variability of the undamaged system components provides a distribution that has to be substituted to the Dirac-δ used so far for such systems. In addition, a damaged situation was modelled by randomly reducing the geometrical and mechanical properties of the ropes and the ring-net. Such reductions are expected when the system undergoes corrosion. It results a decrease of the average performance of about 3%, with an increase of the coefficient of variation, from 4 to 5%. Future tests would stress the single contributions on the effects of the damages in term of capacity reduction.

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References

De Biagi, V., M. Marchelli, and D. Peila (2020). Reliability analysis and partial safety factors approach for rockfall protection structures. *Engineering Structures 213*, 100553.

De la Fuente, D., J.G. Castano, and M. Morcillo (2007). Long-term atmospheric corrosion of zinc. *Corrosion Science 49*, 1420-1436.

EOTA (2018). *EAD 340059-00-0106 European Assessment Document: Falling Rock Protection Kits*. European Organisation for Technical Assessment, Brussels, Belgium.

Govoni, L. and C. Strada,C.(2015). The role of rockfall protection barriers in the context of risk mitigation: the case of the Autonomous Province of Bolzano. In G. Lollino, F. Guzzetti et al. (Eds.), *Engineering Geology for Society and Territory-Volume 5: Urban Geology, Sustainable Planning and Landscape Exploitation*, 397-400. Springer.

Guo, L. P., Z.X. Yu, Y.T. Jin, L.X. Liao, and L.R. Luo (2022).An analytical method for evaluating the deflection and load-bearing and energy absorption capacity of rockfall ring nets considering multifactor influence. *Advanced steel construction 18*, 630-647.

Hoffmann, M., V. Donev, and M. Brauner (2023). Life cycle costs and asset management for protective structures against natural hazards. *ce/papers 6*, 70-78.

Marchelli, M., V. De Biagi, and D. Peila (2020). Reliability-Based Design of Protection Net Fences: Influence of Rockfall Uncertainties through a Statistical Analysis. *Geosciences 10*, 280.

Marchelli, M., V. De Biagi, and D. Peila (2021). Reliability-based design of rockfall passive systems height. *International Journal of Rock Mechanics and Mining Sciences 139*, 104664.

Marchelli, M., M. Paganone, D. Bertolo, V. De Biagi, D. Peila, and S. Vigna (2022). A tool for monitoring rockfall protection works and plan the maintenance: the case of the autonomous region of Valle d'Aosta. *GEAM Geoingegneria Ambientale e Mineraria 166*, 33-41.

Melchers, R.E. (2018). Progress in developing realistic corrosion models. *Structure and Infrastructure Engineering 14*, 843-853.

Pimpinella, F., M. Marchelli, and V. De Biagi (2024, December). A new analytical model to assess the performance of rockfall flexible barriers. Working paper, Politecnico di Torino.

UNI (2018). *UNI 11211-4: 2018 Rockfall protective measures. Part 4: Definitive and executive design.* UNI Ente Nazionale Italiano di Unificazione, Milano, Italy.