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From nominal energy to capacity curves: a probabilistic framework for reliability-based design of flexible rockfall barriers

V. De Biagi, M. Marchelli, F. Pimpinella
Politecnico di Torino, Turin, Italy
valerio.debiagi@polito.it
0000-0003-1866-9362

Abstract

Politecnico di Torino, Italy

Flexible rockfall barriers are widely adopted passive protection systems in mountainous regions, yet their design still relies on deterministic criteria based on Maximum Energy Level (MEL) and Service Energy Level (SEL) tests. These standardized procedures provide a single nominal energy value, which does not reflect the variability of real impact scenarios nor the stochastic nature of barrier performance. This limitation hinders the integration of reliability-based principles into design, a cornerstone of modern structural engineering.

This work merges a probabilistic framework to estimate the mechanical performance of flexible rockfall barriers under a wide range of impact scenarios into the RockStop software, integrating the resulting capacity curve within the software and enabling its practical use in design workflows. The framework derives capacity curves for flexible rockfall barriers and is built upon a generalized multi-component analytical model, developed by the authors, that simulates barrier response under arbitrary impact conditions by assembling analytical representations of each component (net, wire ropes, posts, energy dissipators). A Monte Carlo simulation scheme propagates uncertainties in geometry, mechanical properties, impact position, and component variability, generating a probabilistic description of the barrier's energy absorption capacity. Results show that highly eccentric impacts can significantly alter the nominal capacity. The integration of trajectory outputs, combined with the barrier capacity curve, in RockStop enables site-specific assessment of all possible actions and their frequency, allowing the calculation of failure probability for both newly installed and existing barriers.

This framework marks a major advancement toward risk-informed design by enabling the integration of reliability-based safety formats for rockfall barriers, supporting comprehensive lifecycle performance assessment, and providing a robust basis for quantifying residual risk after mitigation.

Keywords

Reliability-based analysis, Risk mitigation, Rockfall, Software.

1 Introduction

Flexible rockfall barriers are among the most widely implemented passive protection systems for mitigating rockfall hazard in mountainous terrain (Peila and Ronco, 2009). Their mechanical

characterization and certification rely on two standardized full-scale impact tests: the Service Energy Level (SEL) and the Maximum Energy Level (MEL), as prescribed in EAD 340059-00-0106 (EOTA 2018). These tests provide a unique nominal energy capacity for each barrier type, obtained under strictly controlled impact conditions: central impact, fixed block geometry, prescribed velocity, and a specific three-module configuration. While this procedure ensures comparability across products, it also embeds a fundamental limitation: real impact scenarios rarely correspond to the standardized test configuration. In practice, block size, velocity, trajectory height, impact angle and, crucially, impact position, vary widely, leading to markedly different load-transfer mechanisms and structural responses (Yu et al., 2021). Full-scale tests, analytical formulations and numerical simulations consistently show that such variations may induce significant variation in actual barrier capacity compared to the nominal MEL value (Coulibaly et al., 2019).

A second major limitation arises on the action side of the design format. Current national guidelines (e.g., UNI 11211-4:2018; ONR 24810:2021) prescribe the use of single characteristic values derived from trajectory simulations (typically the 95th percentile of block velocity and impact height), assuming a representative block volume, to represent all possible rockfall events. This simplification overlooks the inherently stochastic nature of block mass, kinematics and trajectory height distributions, which may span orders of magnitude depending on site-specific geological and geomorphological conditions. Consequently, the design action is treated as a fixed quantity, although the underlying variability is large and well documented (Bourrier et al., 2016; Macciotta, 2019).

Taken together, these two simplifications (a unique deterministic resistance from MEL testing and a unique characteristic action from trajectory percentiles) make it impossible to quantify the true probability of failure of flexible barriers. Recent reliability-based studies illustrate that the actual failure probability of flexible barriers may vary by orders of magnitude depending on the event frequency, block size distribution, kinematic variability, barrier installation configuration and performances (De Biagi et al, 2020; Marchelli et al., 2020, Marchelli et al., 2021). Neglecting the intrinsic variability of both resisting and acting quantities may therefore lead to designs that are either overly conservative or insufficiently safe. To address these limitations, a dedicated software, RockStop (De Biagi and Marchelli, 2025), has been developed to implement a time-independent reliability-based design framework, allowing designers to compute the failure probability of rockfall barriers by integrating site-specific probabilistic descriptions of impact velocity and trajectory height, derived from trajectory analyses, together with the block mass frequency distribution. In its original formulation, however, RockStop assumes a deterministic resistance, represented by the nominal MEL value, thereby inheriting the limitations of current design practice.

In this work, we enhance the RockStop framework by replacing the deterministic MEL-based resistance with a probabilistic capacity curve, constructed from thousands of simulated impact scenarios. The capacity curve is derived by repeatedly evaluating the barrier's mechanical response under randomized impact conditions, including variations in impact position, block size, geometric tolerances, and component mechanical properties. These simulations are performed using a generalized multi-component analytical model, developed by the Authors (Pimpinella et al., 2025; Pimpinella et al., under review), which captures the full load-transfer mechanism of the system and explicitly accounts for the effects of eccentricity and component-level variability on energy dissipation. By integrating the resulting capacity curve into RockStop, the software transitions from a single-value representation of resistance to a distribution-based description of barrier capacity, ensuring that both actions and resistances are treated consistently within a reliability-based design framework. This upgraded approach enables a truly operational, site-specific assessment of failure probability, grounded in the actual variability of impact scenarios and system response. An illustrative application on an RXI-100 barrier is presented to demonstrate the construction of the capacity curve and its implications for reliability-based design.

2 Methodology

2.1 Generalized Multi-Component Analytical Model (GMCM)

The construction of the capacity curve requires a mechanical model capable of reproducing the behaviour of a flexible rockfall barrier under arbitrary impact conditions while maintaining computational efficiency sufficient to allow thousands of simulations. For this purpose, a Generalized

Multi-Component Analytical Model (GMCM) developed by the Authors is employed (Pimpinella et al., 2025). The model represents the barrier as the assembly of its fundamental mechanical subsystems, namely the intercepting structure, wire ropes, energy dissipating devices, posts, and foundations, each described by analytical relations derived from experimental evidence and numerical modelling. Within the GMCM, the intercepting structure is discretized into sets of equivalent fibres whose axial response reproduces the stiffness and strength of the underlying ring-net or wire-mesh arrangement. The impactor is assumed to interact with the net along a localized region, and the net–rope system transmits the load to the longitudinal and panel ropes. Energy dissipators, arranged along selected rope lines, activate once their characteristic force threshold is reached, contributing to the majority of the energy absorption through controlled plastic deformation. Posts and boundary elements redirect the load through bending and axial mechanisms, with their behaviour included in the model through calibrated force–displacement relations.To account for the possibility of direct impacts on the posts, an *ad-hoc* metamodel, specifically developed to reproduce their behaviour under direct impact, is incorporated to capture the additional energy dissipation mechanisms and deformation patterns observed in full-scale tests and detailed numerical simulations (Pimpinella et al., 2024).

The GMCM adopts an incremental quasi-static formulation, applying the impact load in increasing steps and solving sequentially for the displacements and internal forces within each subsystem. At each increment, the model verifies compatibility of deformation and equilibrium of forces among components, identifying the sequence of activations, yielding, stiffening or softening that characterizes the load path. Mechanical and geometric properties, as well as impact coordinates, enter the analysis as input parameters. When these are varied stochastically within a Monte Carlo scheme, the GMCM computes the absorbed energy for each realization as the work performed along the force–displacement path up to the failure displacement of the system. For each impact scenario, the capacity of the barrier is:

$$C_d = \int_0^{w_u} F(w)\, dw \qquad (1)$$

where $w_u$is the displacement corresponding to the onset of failure in any subsystem. Repeating this procedure over thousands of random impact scenarios produces a distribution of dissipated energies, from which the capacity curve is derived (Pimpinella et al., under review). The GMCM therefore provides the mechanical backbone for quantifying the variability of the resisting side of the reliability problem, explicitly capturing the influence of impact eccentricity, block radius, component dispersion and geometric tolerances on the barrier's energy absorption capacity.

2.2 RockStop module for reliability-based design

To operationalise the probabilistic mechanical characterisation provided by the GMCM, the resulting capacity curve is integrated into RockStop, a software tool originally developed by the Authors (De Biagi and Marchelli, 2025) to implement time-independent reliability-based design of rockfall barriers. From previous releases, RockStop now combines the distributions of block mass, velocity and trajectory height from runout analyses with the event frequency along the slope, with a full probabilistic capacity distribution obtained from the GMCM-based Monte Carlo simulations.

In the reliability formulation adopted by RockStop, the failure probability can be associated with two distinct modes: excessive energy, occurring when the block's kinetic energy exceeds the barrier's energy absorption capacity, and excessive height, arising when the block's trajectory height surpasses the nominal height of the barrier. Assuming a lumped-mass trajectory model the failure probability associated with excessive energy over a timeτ is expressed as:

$$F_k(\tau) = 1 - \exp\left[-\lambda\tau \int_0^{\infty} p_f(\mu)\, f_{mk}(\mu)\, d\mu\right] \qquad (2)$$

where λ is the mean annual frequency of rockfall events, $f_{mk}(\mu)$ is the probability density of block mass (derived from deposit surveys or volume–frequency laws), and $p_f(\mu)$ is the conditional probability of failure given a block of mean mass μ. In the original formulation, $p_f(\mu)$ was evaluated as the probability that the kinetic energy exceeded the deterministic barrier capacity. With the introduction of a capacity curve to assess barrier kinetic energy retention capacity, $p_f(\mu)$ becomes:

$$p_f(\mu) = P(E_d < E_i(\mu, v)) \quad (3)$$

meaning that the probability of failure is obtained by comparing the incoming kinetic energy $E_i = \frac{1}{2}mv^2$ with the full distribution of dissipated energy E_d obtained from the values of C_d. Thus, the resisting term is now treated probabilistically, consistent with the action term.With an expression analogous to Eq. (2), the probability of failure due to excessive trajectory height can be computed. Assuming independence between energy-driven and height-driven failure modes, the total annual failure probability is obtained by summing the two corresponding annual failure probabilities. This value represents the primary output of RockStop when assessing an existing barrier, or the target parameter to be achieved in the design of a new installation.

With the integration of the capacity curve, RockStop now treats both actions and resistances as random variables, enabling reliability-based design in two modes. In "design mode", the user specifies a target annual failure probability, and RockStop identifies the minimum capacity curve (and corresponding barrier product) satisfying this target. In "assessment mode", the software computes the annual failure probability for an existing installation. In both cases, the adoption of the probabilistic capacity curve ensures that the design reflects the true variability of barrier performance across impact locations and component states, rather than a single nominal test result.

3 Example of application

To demonstrate the operational capabilities of the proposed probabilistic framework and its integration within RockStop, an application is carried out for a site located in the North-Western Italian Alps, where recurrent rockfall activity has been documented along a steep granitic slope overlooking a secondary mountain road. Historical records and field evidence indicate the presence of frequent small-to-medium rockfall events, associated with freeze-thaw cycles and differential weathering of jointed rock masses. A preliminary geomorphological survey identified a source area extending between 1050 and 1000a.s.l., with an estimated annual frequency of events equal to λ=0.5 yr^{-1}.

Trajectory simulations were performed using a lumped-mass runout model on the reconstructed slope profile. A total of 5000 trajectories were generated, sampling initial block positions, restitution parameters and rolling conditions within ranges obtained from field observations. At the barrier location, selected at an elevation of 870a.s.l. to maximise interception efficiency, the distribution of impact velocities exhibited a right-skewed shape with a mean of 13.1 m/s and a 95th percentile of 16.2 m/s. Trajectory heights measured at the centre of mass of the blocks showed a 95th percentile of 3.0 m, with sporadic impacts exceeding 3.4 m. Block sizes in the deposition area were surveyed following a four-square homogenisation procedure (Marchelli and De Biagi, 2019), yielding a minimum volume of 0.2 m^3 Pareto-Type I shape parameter equal to 1.9, confirming the dominance of small blocks in the frequency distribution.

Given the expected impact energies and the spatial constraints imposed by the slope, an RXI-100 flexible barrier was selected as a representative protective system. Its nominal MEL is 1000 kJ, and its nominal height is 4.0 m. For the present analysis, the barrier geometry, net characteristics, rope arrangement and dissipator properties were defined according to manufacturer data and previous analytical studies conducted on the same technology. The barrier layout was then introduced into the GMCM-based simulation framework.

A Latin Hypercube sampling was carried out by performing 205 simulations, each representing a distinct impact position. Exploiting the symmetry of the barrier configuration and impact mechanics, impacts were simulated over one quarter of a single module only, with results subsequently extended to the full module. Impact scenarios were defined through random sampling of longitudinal and transverse eccentricities, which were found to be the relevant parameters in barrier's capacity.

For each realisation, the GMCM computed the dissipated energy up to system failure, allowing the construction of the site-specific capacity distribution for the RXI-100 barrier. The dissipated energy was normalised with respect to MEL value E_{MEL}. Fig. 1a illustrates the spatial distribution of the normalised dissipated energy E_d/E_{nom} as a function of impact eccentricity within the analysed quarter-module. The results highlight a pronounced spatial dependency of barrier performance: highly unfavourable eccentric impacts are associated with dissipated energies close to 300 kJ, whereas

configurations characterised by quasi-central impacts and symmetric activation of the longitudinal dissipators may exceed 1500 kJ. Overall, only 19 % of simulated impacts resulted in a dissipated energy exceeding the nominal MEL, confirming the strong sensitivity of barrier capacity to impact location, consistently with previous probabilistic investigations.

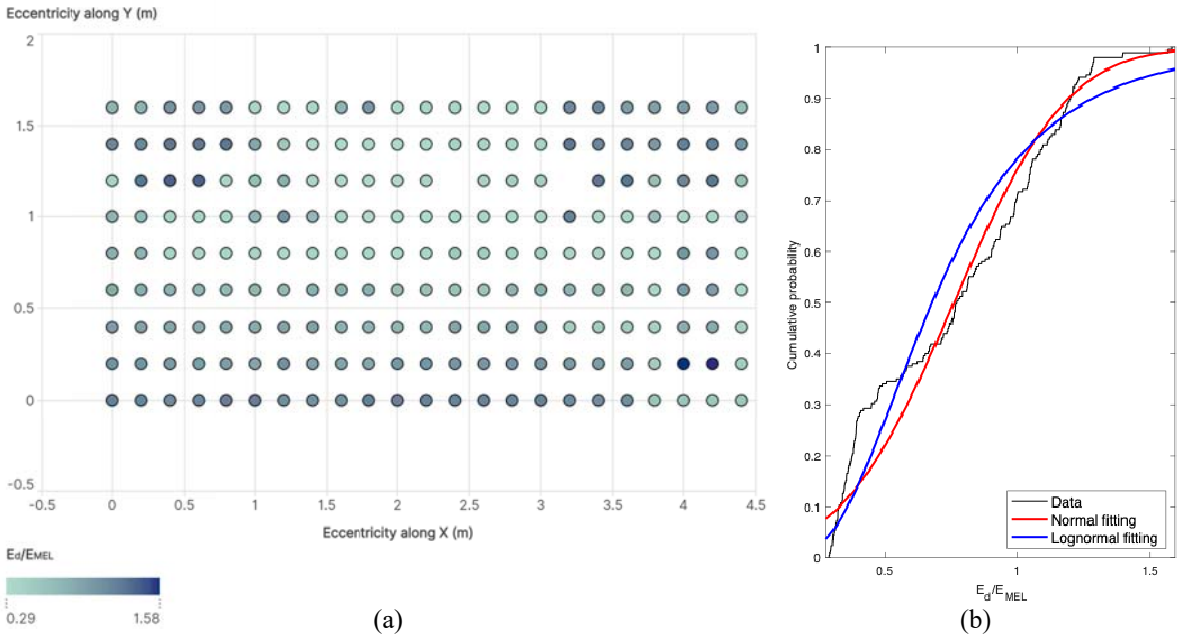


Fig. 1 (a) Spatial distribution of the normalised dissipated energy E_d/E_{MEL} as a function of longitudinal (X) and vertical (Y) impact eccentricity, obtained from LH simulations performed on one quarter of a barrier module. In (b), the empirical cumulative distribution and its normal and lognormal fittings are reported.

By aggregating all simulated impact scenarios, the empirical cumulative distribution of the normalized capacity E_d/E_{MEL} was derived. A statistical fitting procedure showed that this cumulative distribution is best approximated by a normal distribution (red curve in Fig. 1b, with mean and CoV equal to 0.76 and CoV equal to 0.4435), providing a compact probabilistic representation of the barrier capacity. This probabilistic capacity curve was subsequently implemented in RockStop together site-specific distributions of block mass, trajectory height and impact velocity at the barrier location. The conditional failure probability for each potential impact event was evaluated by comparing the incoming kinetic energy with the probabilistic resisting energy, and the total annual failure probability was computed within the time-independent reliability framework. For the RXI-100 barrier at the considered site, the resulting annual failure probability was equal to 1.0×10^{-2}, with energy-driven failures providing the dominant contribution due to the relatively high proportion of impacts characterized by unfavourable eccentricities. Recalculating the risk after installation of the barrier yields a residual risk for the protected road of the order of 10^{-5}, consistent with the individual life safety tolerability thresholds specified in UNI 11211-2 (2021).

4 Conclusions

This work presented a probabilistic framework for the mechanical and reliability-based assessment of flexible rockfall barriers, overcoming the limitations of conventional MEL-based deterministic design. By coupling a generalised multi-component analytical model with Monte Carlo simulations, the variability of barrier performance under arbitrary impact conditions was quantified and synthesised into a capacity curve that more realistically represents the resisting behaviour of the system. Integration of this probabilistic resistance model into RockStop enables a consistent treatment of actions and resistances as random variables within a time-independent reliability framework. Application to an RXI-100 barrier in a representative Alpine setting demonstrated that impact eccentriccity and component-level variability have a strong influence on system capacity and failure probability, with the resulting annual failure probability shown to be compatible with acceptable thresholds for individual risk when appropriately calibrated. Overall, the proposed framework supports transparent, site-specific and performance-based design of flexible rockfall barriers, providing a robust tool for the assessment and optimisation of both new and existing installations. Future developments may extend the methodology to account for ageing effects and component degradation during time.

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