



Politecnico
di Torino

ScuDo

Scuola di Dottorato - Doctoral School
WHAT YOU ARE, TAKES YOU FAR

Doctoral Dissertation

Doctoral Program in Civil and Environmental Engineering (38th cycle)

Mechanical characterization of flexible rockfall barriers through a global multi-component analytical framework

By

Francesco Pimpinella

Supervisor(s):

Prof. Valerio De Biagi, Supervisor

Dr. Maddalena Marchelli, Co-Supervisor

Doctoral Examination Committee:

Prof. Igor A. Chaves, University of Newcastle, NSW, Australia

Dr. Antonio Pol, Inrae, Montpellier, France

Prof. Daniele Peila, Politecnico di Torino, Italy

Politecnico di Torino

2026

Abstract

Flexible rockfall barriers represent one of the most effective protection systems for mitigating rockfall hazards in mountainous regions, coastal slopes, and open-pit mining environments. Their primary function is to safeguard exposed infrastructure and human activities by intercepting and retaining falling blocks before they reach vulnerable areas. To achieve this, the barrier system must dissipate or transform the kinetic energy of the impacting block through its various components, which typically include an intercepting element (such as a steel wire net), supporting structures like wire ropes and posts, energy-dissipating devices, and anchoring elements that ensure stability within the ground.

Today, these barriers are commercialized as complete systems, or kits, and classified as construction products. Consequently, their performance must be verified according to standardized procedures defined by European Assessment Documents (EAD 340059-00-0106, 2018) and earlier guidelines (ETAG 027, 2008). Certification relies on full-scale impact tests, where a block of prescribed geometry strikes the barrier at a single, central position with purely translational kinetic energy. While this approach enables consistent comparison among different technologies, it only reflects a limited set of loading conditions and does not capture the variability of real-world impacts, which may occur at different positions and involve rotational energy.

Designers tasked with mitigating rockfall risk must therefore select a certified product based on its declared performance, e.g. height and energy absorption capacity, derived from these standardized tests. However, because the design process is largely internal to manufacturers and the standardized tests do not encompass all possible impact scenarios, uncertainties remain regarding the barrier's behaviour under real impact conditions.

Recently, some manufacturers have begun conducting additional impact tests at alternative positions along the barrier to better capture variability in real-world conditions. However, due to logistical and economic constraints, the number of these tests remains limited. In parallel, researchers are developing advanced numerical models to simulate a broader range of impact scenarios, aiming to complement experimental data and improve predictive capabilities. These models are typically tailored to specific barrier systems, requiring significant effort to build and calibrate each one, and they involve considerable computational costs. To overcome these limitations, metamodels have recently been introduced; while they offer promising efficiency gains, they demand a large dataset of cases for proper training and still struggle to accurately identify failure locations or stress distribution on individual components. For these reasons, analytical models currently appear to be the most practical and cost-effective solution for preliminary design and performance assessment. At present, a limited number of analytical models exist, predominantly derived from geometric idealisations and/or component-level test results. These formulations are difficult to generalise across diverse technologies and typically fall short of resolving not only global failure conditions but also the stresses, demands, and capacities of the individual components that govern system behaviour.

This thesis therefore aims to develop a holistic performance-evaluation methodology for flexible rockfall barriers across a range of loading scenarios through a global analytical model that is adaptable to multiple products. The proposed framework defines dedicated analytical mechanical representations for each principal component (intercepting net, rope systems, posts, energy dissipators), and assembles them according to the transfer of forces and displacements within the resisting mechanism. While the global model is conceived to be adaptable to different barrier products, achieving adaptability requires knowledge of the specific characteristics of each technology. Where necessary, ad-hoc tests or numerical simulations on individual components are conducted to refine these representations and calibrate the mechanical and geometric parameters governing their response. The resulting analytical model can then be employed to investigate the global response of the barrier system and also to analyse the behaviour of individual components under a wide range of possible loading conditions. Developing such a model has required an extensive and detailed study within this thesis, encompassing both the mechanics of the constituent elements and their interaction within the assembled system.

Once established, the model enables the consideration of all plausible impact scenarios and, for each barrier type, the intrinsic geometric and mechanical variability. Through a large number of simulations, this approach allows the definition of a barrier capacity curve, i.e. a synthetic yet informative representation of system performance, which can effectively replace the single performance value currently provided under EAD certification, offering a more comprehensive and versatile basis for design and assessment.

As a practical application, the proposed framework has been implemented for a specific barrier, RXI-100 (Geobruigg AG), for which full-scale test data were available. This case study illustrates the process of assembling the global analytical model and deriving the system's mechanical compliance curve under generic loading conditions. For selected structural components, ad-hoc experimental tests and dedicated numerical simulations have been carried out to characterise their mechanical behaviour and calibrate the analytical representations. The global model has then been assembled and compared with available full-scale impact test results. In addition, a barrier capacity curve has been generated to demonstrate the potential of the approach. To further verify its robustness, a detailed numerical model of the same barrier was developed and used to simulate loading conditions different from those of the full-scale test, enabling a comparative assessment of the analytical framework under varied scenarios.

Beyond its application to design scenarios, the proposed framework proves instrumental in assessing the condition of existing barriers and estimating performance degradation over time. By introducing specific deterioration mechanisms into the component models, the methodology enables the prediction of residual service life and the evaluation of system capacity under ageing conditions. This capability supports the quantification of residual risk to protected assets, thereby enhancing the reliability of long-term risk mitigation strategies and improving public safety. In addition, the approach offers a scientifically grounded basis for maintenance planning and prioritisation, ultimately contributing to more informed decision-making for the sustainable management of protective infrastructure.