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## A PROBABILISTIC APPROACH TO INTEGRATE THE EFFECT OF PROTECTION SYSTEMS INTO ROCKFALL HAZARD ASSESSMENT

David Toe<sup>1</sup>, Alessio Mentani<sup>2</sup>, Franck Bourrier<sup>1</sup>, Laura Govoni<sup>2</sup>, Guido Gottardi<sup>2</sup>, Stéphane Lambert<sup>3</sup>

The paper introduces the essential features of a new strategy to develop reliable and computationally cost-effective models of the mechanical response of a rockfall barrier subjected to realistic impact conditions. The approach combines the use of three-dimensional, non-linear and dynamic finite element models of a rockfall barrier with a reliability-based probabilistic approach. The strategy may apply to any type of rockfall barrier in presence of any condition of impact and it is devised so it can be implemented in rockfall propagation simulation tools. Applications of the approach are wide and includes the evaluation of the residual hazard down existing protection works and the reliable planning of new interventions.

**Keywords:** rockfall hazard, FEM, non-linear dynamic analysis, probabilistic approach, protection structures

### INTRODUCTION

Rockfall propagation simulation tools generally use a process-based probabilistic approach to predict the energy and the trajectories of blocks falling along potentially unstable slopes. These tools play a crucial role in rockfall hazard assessment and design of mitigation interventions. The effect of the protection structures is described within these tools by a location, a height and a capacity [1, 2]. The value of capacity, which might not be available, is given as a result of full-scale tests on prototypes carried out in standardised conditions, assuming that impact parameters other than the kinetic energy have no influence on the barrier ultimate response. Suitably calibrated and developed numerical models of these structures [4, 5] could certainly allow a more comprehensive description of the rockfall barrier within these tools through a simulation of the likely response of the barrier during each rockfall propagation. However, the high computational cost associated to a procedure as such would make the approach unpractical. On the other hand, in order to have a reliable prediction of the residual hazard down the structure, the effect of impact conditions on the structure response should be accounted for. This is especially crucial for semi-rigid, low to medium energy barriers (less than 250 kJ), whose capacity have been shown to be very much dependent on the impact conditions [6, 7, 8]. In this context, a strategy to develop reliable and computationally cost-effective models of the mechanical response of a rockfall barrier subjected to realistic impact conditions is presented with reference to a semi-rigid barrier currently installed within the Alpine arc. Numerical analyses carried out in ETAG-like conditions, which involved the cen-

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tral impact of a prismatic block of length equal to one third of the barrier height, showed that the barrier capacity was about 200 kJ. The FE model was then subjected to further 600 simulations in which the impact related parameters were varied within a range typical of rockfall trajectory analyses. Results were used to build a meta-model of the barrier response. The scope of the meta-model is to reproduce the barrier effect for any impact event into a common rockfall simulation model. The meta-model uses a reliability-based approach and provides, for a low cost-efficiency ratio, the response of the structure in terms of its ability in stopping the block and residual block kinetic energy in case of structure failure.

## FE INVESTIGATION OF THE PERFORMANCE OF A SEMI-RIGID BARRIER

Rockfall protection barriers are structures composed by a certain number of single functional modules. Each module is made of an interception structure, a supporting structure and connecting components. In the following, a semi-rigid barrier is analysed with the aim of predicting its response to impact events. The studied barrier is 3.2 m high with three modules of 5 m width each [10]. The principal interception structure, composed by 15 longitudinal cables of 12 mm diameter, is connected to the posts, which constitute the supporting structure. Internal and lateral posts are IPE 200 and IPE 300, respectively. As secondary interception structure, a double-twisted hexagonal meshwork is installed. Whereas its presence is not of interest when modelling flexible barrier with high energy absorption capacity, it can considerably affect the performance of semi-rigid systems [10]. Finally, side cables of 18 mm diameter connect the head of the lateral posts to the ground (Fig. 1).

The numerical model is built using one-dimensional elements with elasto-plastic constitutive laws assigned to each element. Details of the mechanical properties are provided in [10], while the behaviour of the double-twisted mesh refers to [7]. The barrier is considered installed vertically to the ground. 600 non-linear explicit dynamic simulations, with different loading conditions, are carried out to investigate its response to polyhedral shaped impacting bodies. Analyses were run by varying five parameters of the event conditions: the block volume, translational and rotational velocities, impact point position and inclination of the incident trajectory. The system is considered failed when the block is not arrested and goes beyond the structure. Figure 2 illustrates the results of the simulations in terms of block volume and horizontal velocity at impact. Green symbols represent cases where the block was arrested, while the other colours indicate the failure mechanisms associated to each simulation.

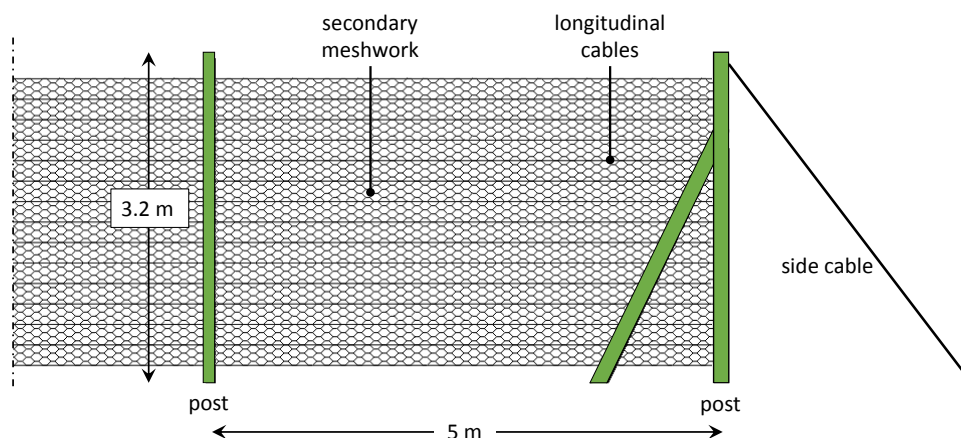


Fig. 1 The semi-rigid barrier studied (half model)

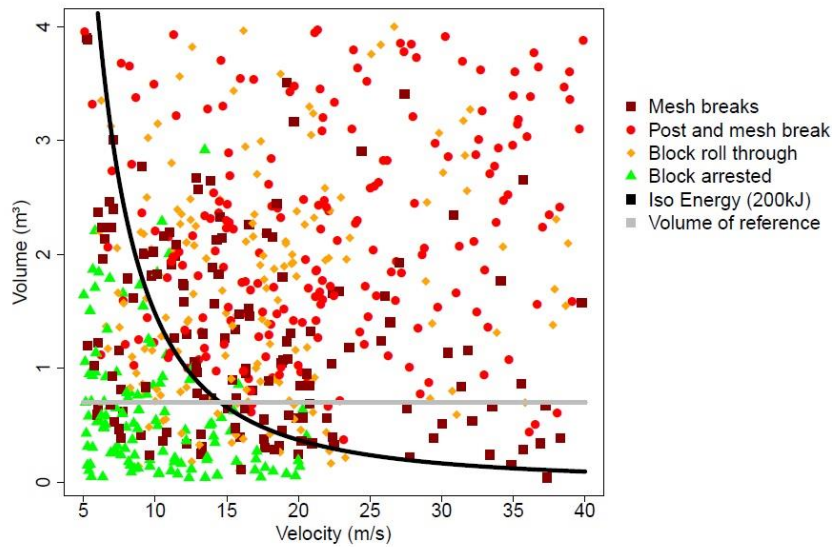


Fig. 2 FEM results of simulations to different impact events

When rupture of the system is reached, red dots stand for failure of the posts, while brown nodes are cases for which the mesh failed after the block passed through the longitudinal cables and orange symbols represent for the cases where the block rolls over the structure (i.e. block impacting the mesh at the top). The black curve represents the limit energy level identified in [10]. Similarly, the grey line is the maximum volume to be considered following [9] (i.e. 1/3 of barrier nominal height).

It can be seen that none of these two lines allow differentiating failure and non failure cases. In particular, a significant number of mesh ruptures are observed below these limits. This demonstrates that, due to the high dependence of the structure performance on the impact conditions, currently used design methods based on deterministic approaches fail in addressing the performance of a semi-rigid barrier. The FE model helps to identify the barrier behavior, both in case of failure or not. On the other hand, it also provides several data for each simulation about the post-impact trajectory of the block. These data can be implemented in a probabilistic approach to create a meta-model of the barrier, able to predict its response for every impact event, as illustrated in the next section.

## PROBABILISTIC MODEL OF THE BARRIER RESPONSE

The probabilistic approach allows developing a meta-model of the response of the structure. It basically corresponds to the response envelop of output parameters depending on the 6 parameters defining the impact conditions. The response is addressed in terms of structure capacity in arresting the block, via the performance function  $G$  proposed in [11], and residual energy of the block if not stopped by the barrier. For example, Fig. 3 (a) gives the cumulative probability of these two variables in the case of the structure presented previously and considering the widest possible ranges for the 6 input parameters.

The meta-model of the response of the structure may be implemented into block propagation models to integrate the effect of the protection structure. Such improved propagation model can be used to quantify the efficiency of protection structures on endangered sites. This quantitative assessment of structure efficiency is of major interest for the optimal design and location of protection structures.

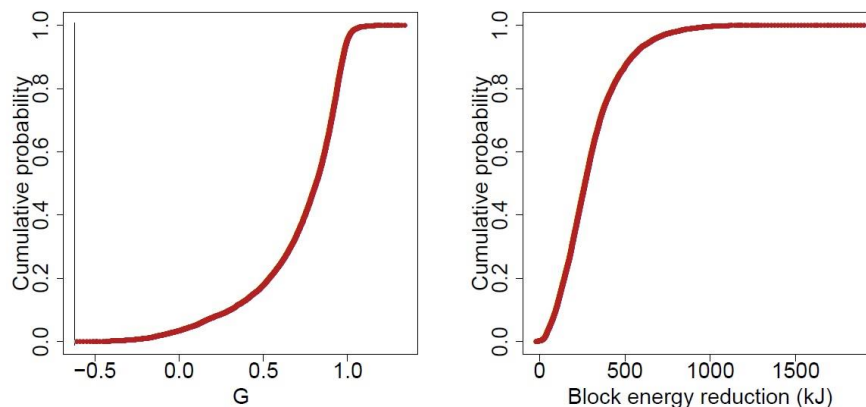


Fig. 3 Meta-modeling results in terms of (a) performance function  $G$  and (b) block kinetic energy reduction.

## CONCLUSION

The combination of three-dimensional, non-linear and dynamic finite element models of a rockfall barrier with a reliability-based probabilistic approach presented allowed developing computationally efficient meta-model of the response of the structure. This meta-model allows assessing the structure capacity in arresting the block and the residual energy of the block if not stopped by the barrier.

It can easily be implemented into block propagation models to integrate the effect of the protection structure. Such an improved propagation model can be used to quantify the efficiency of protection structures on endangered sites. This quantitative assessment of structure efficiency is of major interest for the optimal design and location of protection structures.

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