A Novel Approach to Assess the Ability of a Protection Barrier to Mitigate Rockfall Hazard

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The paper presents a novel approach to assess the ability of a protection barrier to mitigate rockfall hazard. Using a meta-modeling approach, a simplified model of a widely used type of rockfall protection barrier was developed to predict the barrier capability to stop the block. A meta-model was created based on FE simulation results considering six input parameters relevant for the wide variety of impact conditions observed on natural sites. The meta-model was then used in combination with a rockfall trajectory simulation tool to evaluate the efficiency of the barrier to mitigate rockfall hazard for two real cases. The results of the study reveal that the meta-model is effective to accurately predict the response of the barrier for different impact conditions. In addition, the coupling of the meta-model with a rockfall trajectory simulation tool provides a better assessment of the barrier efficiency compared to classical design guidelines as it accounts for the distribution of the various parameters describing the block incident trajectory. This approach appears promising to improve rockfall quantitative hazard assessment and optimize rockfall mitigation strategies.

Key words: rockfall mitigation, barrier, meta-model, rockfall simulation

1. INTRODUCTION

Various types of rockfall countermeasures can be used to intercept falling blocks such as barriers, nets and embankments. There is a growing demand in considering the real effect of these protection structures on rockfall trajectories, both for protective structure design and risk assessment. There is thus a strong need for developing tools and methods that can integrate the protective effect of these structures in rockfall trajectory simulation tools.

The most versatile and widely used protection structures are rockfall protection barriers. In practice, the design of a barrier for a given site is done by comparing the barrier reference capacity to the the block kinematic energy at the barrier location as obtained from rockfall simulations. The barrier reference capacity may be determined based on the European guidelines ETAG 027 [*Eota*, 2013]. However this design approach does not account for the wide variety of loading cases resulting from the block kinematics (translational velocity, rotational velocity, impact angle, impact position). In the end, a simple ETAG 27-based design may lead to inefficient barriers.

Quantifying the response of the barrier for different loading conditions requires complex and time consuming modeling approaches (Finite Element Method (FEM) or Discrete Element Method (DEM)) [*Nicot et al.*, 2001; *Volkwein*, 2005; *de Miranda et al*., 2010; *Bertrand et al*., 2012; *Gentilini et al*., 2012; *Gentilini et al*., 2013; *Escallon et al*., 2014; *de Miranda et al*., 2015; *Bourrier et al*., 2015b; *Mentani et al*., 2015; *Coulibaly et al*., 2017]. These models can hardly be directly coupled with classical rockfall trajectory analysis models due to their high computational cost. To overcome this problem, meta-models which can mimic the behavior of complex models with reduced computational time can be created [*Sudret*, 2008; *Blatman and Sudret*, 2010; *Mollon et al*., 2011]. In the context of rockfall protection structures, the meta-model is dedicated to model the barrier response to varying impact conditions. This approach is already widely used in civil engineering [*Jin et al*., 2001; *Farhang-mehr and Azarm*, 2005;

Gonzalez-Perez and Henderson-Sellers, 2008; *Toe et al*., 2017]. Applications in the field of rockfall protection structures were addressed by *Bourrier et al*., 2015b, *Mentani et al*., 2016 and *Toe et al*., 2018.

This study is dedicated to the development and evaluation of a new approach to integrate variable and realistic impact loading conditions into the assessment of the barrier efficacy. It considers a low-energy barrier for which a FEM model is available. First, a meta-model is created based on the FEM model simulation results, considering input parameters relevant to realistic impact conditions. Then, the meta-model is used to evaluate the effectiveness of the barrier in stopping blocks for two real rockfall scenarios. Finally, the advantages and limitations of this approach are discussed and compared to current practice in protection structure design.

2. MATERIALS AND METHODS

2.1 Barrier model and simulations

2.1.1 Finite Element model

The cable-net barrier was model using the Finite Element (FE) modeling approach and the commercial code Abaqus [*Abaqus*, 2013]. For this barrier type, the interception structure is made of longitudinal cables, connected to steel posts fully restrained at their base. The structure type is provided with a secondary hexagonal meshwork fastened to the longitudinal cables.

The study considers a three spans, 5 m spaced, cable-net barrier of 3.2 m reference height (**Fig. 1a**). Longitudinal cables, 12 mm in diameter, pass through the internal posts (IPE 200) and are knotted to the external posts (IPE 300), connected to the ground by side cables of 18 mm diameter. A secondary meshwork, made of a double twisted hexagonal mesh is connected to the top and bottom longitudinal cables with steel wires. The FE model of the barrier is three-dimensional and made of one-dimensional elements, whose behavior is governed by elasto-plastic constitutive laws. The mechanical response of the barrier elements was described based on available results of laboratory tests in *de Miranda et al*., 2015. Particular attention was devoted to model the behavior of the wires within the hexagonal mesh, following data of experiments carried out on mesh portions [*Thoeni et al*., 2013; *Mentani et al*., 2015]. The posts behave following an elastic-perfectly-plastic law up to a failure limit, cables harden in the plastic phase and may undergo indefinite deformations once a second yielding threshold is attained. Mesh wires are prescribed to soften prior to failure.

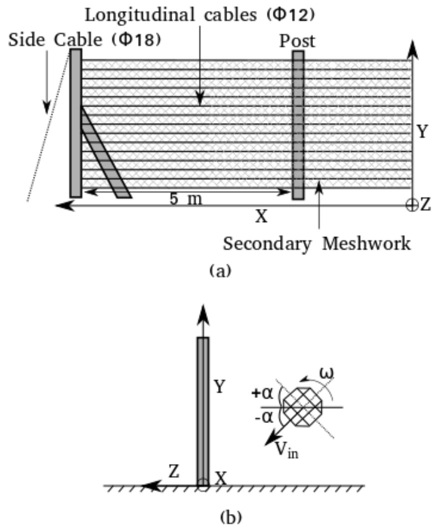

Fig. 1 Geometry and impact conditions for the cable-net protection barrier: a) back view and b) side view.

2.1.2 FE simulations

The reference capacity of the barrier was defined in accordance to the procedure described in Annex A of ETAG 027 [*Eota*, 2013]. Simulations of a centered impact with a block translational velocity of 25 m/s and no rotational velocity were considered. The maximum block mass for which all the Guideline requirement were fulfilled was found equal to 640 kg yielding to a reference capacity of 200 kJ for the cable net barrier.

Six input parameters were considered for creating the meta-model: the block volume V; the block impact position on the barrier X and Y; the incident angle of the impact α; the translational velocity v; and the rotational velocity ω (**Fig. 1**). The parameters were sampled in ranges adapted to the reference barrier capacity (**Table 1**). A free-board was considered to avoid direct impact of blocks on the top cable. Latin Hypercube (LH) sampling method [*Sacks et al*., 1989; *Fang et al*., 2005] was used to minimize the number of simulation runs needed to build the meta-model and to keep an optimized sample along the range of each input parameter. This sampling resulted in 280 simulations carried out.

Table 1 Input parameters for loading condition

Input parameter	Unit	Range Min-max
Translational velocity, *v*	m/s	5 – 22.5
Rotational velocity, *ω*	rad/s	0 - 35
Volume of the block, *V*	m^3	0.03 – 2.5
Incident angle, *α*	deg	-60 - 60
Impact position, *X*	m	0 - 7.5
Impact position, *Y*	m	1 – 2.5

2.2 The meta-modelling approach

The developed meta-model can be assimilated to a mathematical operator describing the response of the cable-net barrier while accounting for multiple input variables. Due to its mathematical structure and negligible computational cost, the meta-model can be easily coupled with a probabilistic rockfall trajectory simulation tool.

The meta-models were developed using the results of the FE simulations carried out on the cable-net barrier with the input parameters ranges defined in **Table 1**. Within the context of this study, the meta-model is developed to predict two possible events: success or failure of the barrier to stop a block. These events are grouped in two classes: class B_{Succ} for arrested blocks and class B_{Fail} for blocks passing the barrier. As dealing with two classes, a Support Vector Machine (SVM), was used for creating the meta-model [*Brereton and Lloyd*, 2010; *Kausar et al.*, 2011].

2.2.1 Support Vector Machine

The Support Vector Machine (SVM) approach is based on statistical learning theory [*Vapnik*, 1995], and can be used to build a meta-model which can predict the class of an output data (success/failure of the barrier in this study).

The basic SVM approach (M_{SVM}) consists of defining, in a space of input parameters, the optimal hyper-plane separating the regions associated with the considered classes. For that purpose, among all points of the space only those that are closest to the hyperplane, called support vector, are considered. The optimal hyperplane is defined as the hyperplane whose margin, i.e. distance from these closest points is maximal. It is thus calculated by maximizing the distance from the hyperplane to the closest points on each side.

The optimal definition of the hyperplane can require non-linear transformation of the data to another space of potentially higher dimension using kernel functions [*Baudat and Anouar*, 2001].

In this study, the space of the input parameters corresponds to the different parameters associated with the impact conditions. Linear and radial kernels have been used to build accurate meta-models (function *svm* in R (V 3.2.3) package *e1071*).

2.2.2 Error quantification

The developed meta-model accuracy was estimated by comparison with the data obtained from the FE simulations described Section 2.1. The meta-model prediction error was estimated using the leave-one-out cross validation method [*Allen*, 1971].

The global accuracy of the meta-model ($Q(M_{SVM})$) is evaluated using n results $M(x_i)$ from the FE model simulations. For each parameters combination x_i, a meta-model is created using all FEM simulation results except $M(x_i)$. The meta-model prediction for x_i ($M^i_{SVM}(x_i)$) is compared to the remaining result $M(x_i)$ observed from the FEM simulations. This comparison is repeated for all x_i ranging between x_1 and x_n.

$$Q(M_{SVM}) = 1 - \frac{1}{n}\sum_{i=n}^{n} M(x_i) - M^i{}_{SVM}(x_i) \quad (1)$$

The quality of the meta-model is also estimated regarding the misclassification rate defined as follows. With reference to the FE observations, the SVM based meta-model can provide bad (false, *F*) or good prediction (true, *T*). As described in **Table 2**, a good prediction is either positive (*TP*) when barrier success (B_{Succ}) is both estimated and observed or negative (*TN*) when barrier failure (B_{Fail}) is both estimated and observed. Similarly, a false prediction is either positive (*FP*) when barrier success is estimated while failure was observed or negative (*FN*) when barrier failure is estimated while success was observed. Based on these definitions, two indicators were used to discuss the performance of the meta-model: the false negative rate ($FN_r = FN / (FN+TP)$) and the false positive rate ($FP_r = FP / (FP+TN)$). In the context of this study, the false positive rate is the most relevant to deal with as it focuses on the most critical situation. Indeed, a high FP_r value is associated to an overestimation of the barrier capacity by the meta-model.

2.3 Practical evaluation of the barrier efficiency using the meta-model

The objectives of this section are to evaluate the accuracy of barrier design for two rockfall scenarios following current practice and using the meta-modeling approach. First, two rockfall scenarios were selected to test the influence of the loading conditions on the barrier efficacy. The scenarios were chosen so that the blocks reach the barrier with a maximum translational kinetic energy around the reference capacity of the barrier as previously determined. Then, the ability of the barrier to stop blocks in the two scenarios is evaluated using rockfall trajectory simulations coupled with the meta-model presented in section 2.2.

Table 2 Definition of cases for assessing the meta-model performance

	SVM prediction	
FE observation	B_{Fail}	B_{Succ}
B_{Fail}	*TN*	*FP*
B_{Succ}	*FN*	*TP*

The considered real-case site is located in the 'Forêt communal de Vaujany' in the French Alps. The scenarios focus on protecting a forest road located on the slope (38°) from cubic blocks (volume: 0.1 to 1 m^3). On this site, rockfalls are reactivated from small topographical outgrowths as indicated in *Bourrier et al*., 2015a. In the first scenario (SCR1) the release area of the block is located at mid slope (130 m from the road) in a snow avalanche corridor (**Fig. 2**). The barrier position is projected 60 m below the release area. In the second scenario (SCR2) the release area of the block is located 100 m above the road and the barrier is located just above the road.

Rockfall simulations were conducted using the 3D rockfall model RockyFor3D (RF3D) [*Dorren*, 2015]. RF3D is a model that simulates block trajectories on forested or non-forested slopes. The model simulates the propagation of spherical blocks along a slope modeled as a Digital Terrain Model (DTM) in raster format. The block propagation is modeled by a succession of free flights, impacts on the slope surface and impacts on trees. The rolling motion of the block is considered as a succession of rebounds and the sliding of the block over the slope surface is not taken into account. The parameters governing the block rebound had been defined according to field measurement campaigns done in previous study [*Dorren et al*., 2006; *Bourrier et al*., 2009; *Bourrier et al*., 2015a].

10 000 blocks were released for each scenario. The initial falling height of the block was set at 0.5 m. In the numerical model, two lines of measure were defined at the location of the rockfall barriers in order to register the blocks kinematic parameters (6 parameters presented in **Table 1**). The 6 blocks kinematic parameters presented in **Table 1** were recorded along measuring lines along the barrier location. The barrier meta-model was then used considering these records to evaluate the barrier efficacy.

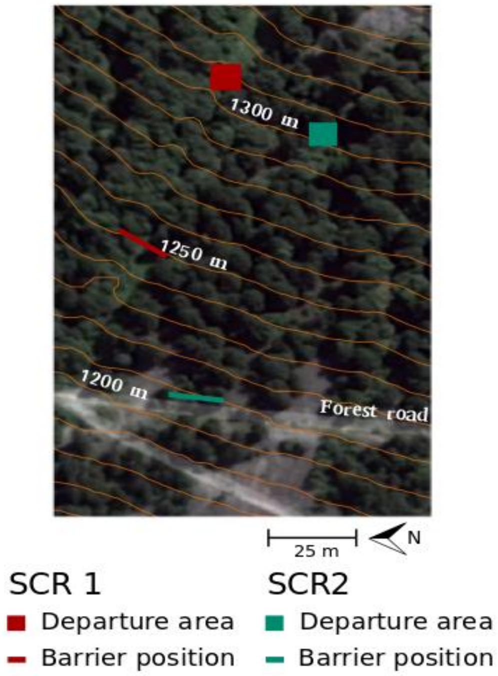

Fig. 2 Presentation of the two rockfall scenarios.

3. RESULTS

3.1 FE simulations results

In **Fig. 3**, the results of the FEM model simulations are grouped on the block translational velocity-block volume plane. Four types of block-barrier interactions were observed depending on the loading condition:

- The block is arrested by the barrier.
- The block passed the barrier by rolling over it.
- The block passed the barrier as a result of the perforation of the secondary hexagonal meshwork.
- The block passed the barrier as a result of the failure of the whole structure.

Over the 280 simulations, the barrier succeeded in stopping the blocks in 61 cases. The barrier inefficiency observed in the 219 other cases resulted from block rolling over (78 cases); mesh perforation (66 cases) and barrier global failure (75 cases).

On the whole, the prevailing parameters in the barrier response are the block velocity and mass, the influence of other impact parameters being limited (**Fig. 4**). Nevertheless, some trends are worth being highlighted. For negative values of incident angle (upward trajectory), the rolling over mechanism is prevailing. Arrested blocks tend to concentrate for low translational/rotational velocities. A higher number of global failure cases are observed close to the post (*X*-axis position). A slight decrease in block arrest is observed increasing the impact point position (*Y*-axis) for impact velocities above 10m/s. These trends illustrate the complexity of the barrier response when varying the impact conditions.

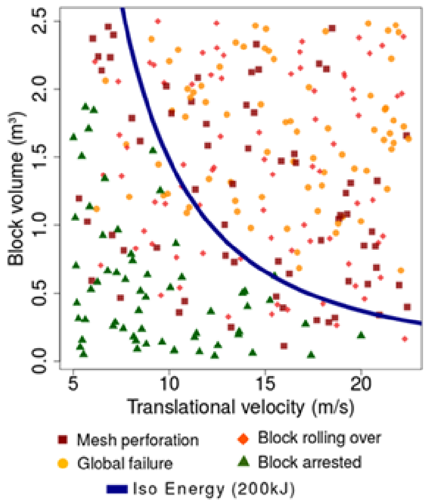

Fig. 3 Influence of block volume and translational velocity on the block-barrier response.

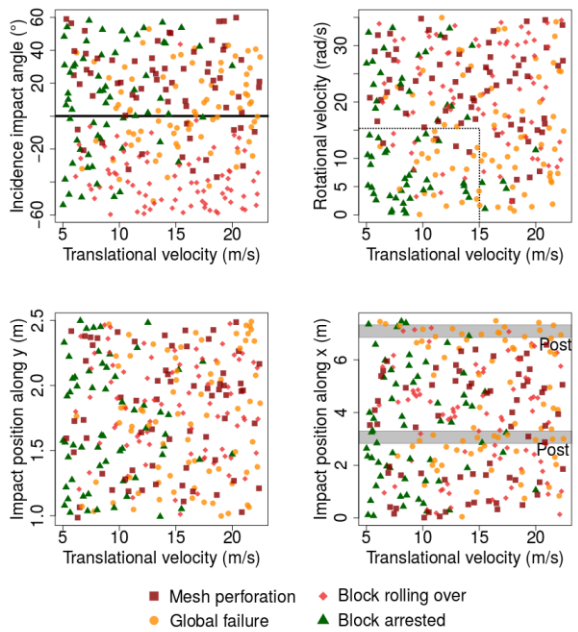

Fig. 4 Block-barrier interaction mechanisms: a) block rolling over; b) mesh perforation and c) global failure.

3.2 Meta-models quality evaluation

The meta-model was created using the plan of experiments consisting of 280 combinations of the 6 input parameters (**Table 1**). Its validation was pursued by comparison with the results from the FE simulations.

Table 3 Quality evaluation for the meta-model created

	Prediction		
Observation	B_{Fail}	B_{Succ}	
B_{Fail}	213	6	FR_r = 3%
B_{Succ}	16	45	FN_r = 27%

The accuracy of the model was evaluated according to eq. 1 and resulted in M_{SVM} equal to 92%. The meta-model failed to predict 16 barrier success over 61 (FN_r = 27%) and failed to predict 6 barrier failures over 219 (FP_r = 3%) (**Table 3**). Over these 6 misclassified cases, 5 are related to mesh perforation and 1 is related to global failure (**Fig. 5**). This indicates that the meta-model overestimates the barrier capacities as 3% of the failure cases are not predicted.

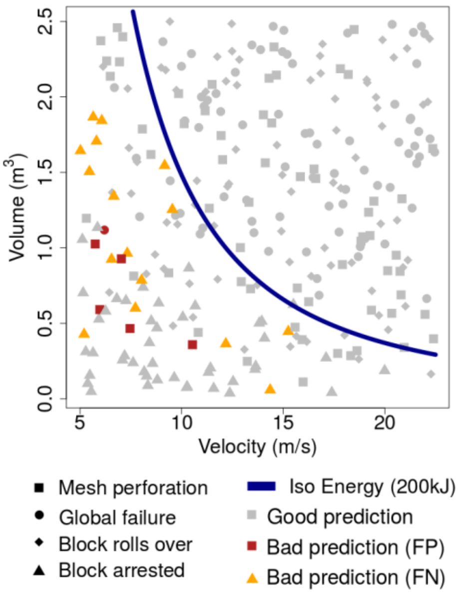

Fig. 5 Prediction of the B_{Succ} and B_{Fail} for the narrow range scenario. Good and bad predictions are indicated by grey and red symbols receptively. The shape of the symbols indicates the mode of failure.

3.3 Estimation of the barrier efficiency

Over the 10,000 rockfall simulations only 2,677 blocks reach the barrier location for SCR1 and 4,712 blocks reach the barrier location for SCR2. For the two scenarios, 95% of the blocks reaching the line of measure had energy below 200 kJ which confirms the choice of this low energy barrier.

The distributions of the block kinetic parameters registered at the two barriers locations are presented (**Fig. 6**). These distributions show significant differences in the block kinematic parameters depending on the scenario. The block impact heights are smaller in SCR2 (0 to 1m) compared to SCR1 (0 to 2.5m). The incidence impact angle ranges between 20 to 40° for SCR2 and between 40 to 80° for SCR1. In SCR2 rotational velocities are slightly larger (10 to 30 rad/s) compared to SCR1 (5 to 20 rad/s). The block volume distribution are more spread for SCR2 with volume ranging between 0.3 to 1 m^3 compared to ranges between 0.55 to 1 m^3 for SCR1.

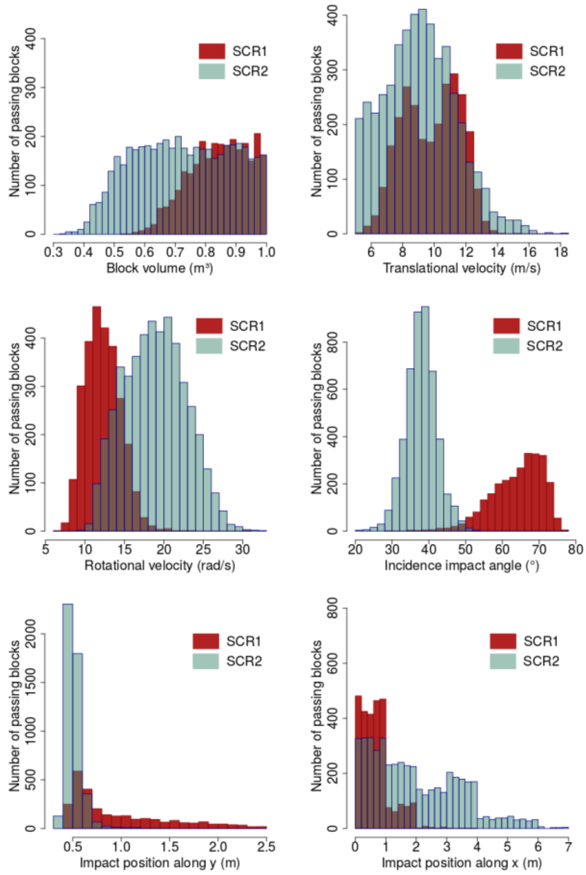

Fig. 6 Distribution of parameters measured at the barriers location from rockfall simulations.

The impact position along the *X*-axis is more spread for SCR2 with block impact distributed from the center to the edge of the barrier compared to block impact positions located around the center of the barrier for SCR1. Finally, only small differences are observed between the two distributions of block translational velocity.

Fig. 7 presents the meta-model predictions for the two rockfall scenarios. For SCR1 the meta-model predicted that 131 blocks (5.3%) lead to barrier failure. Among these, 84 blocks (3%) are below the 200 kJ limit. On the opposite, 37 blocks (1.3%) lead to barrier success above the 200 kJ limit. For SCR2, the meta-model predicted that 2248 blocks (47.5%) lead to barrier failure, with 42% of the blocks below the 200 kJ limit. 5% of the blocks lead to barrier failure above the 200 kJ limit.

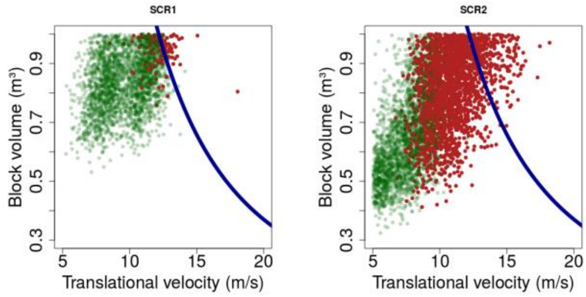

Fig. 7 Prediction of the B_{Succ} (green) and B_{Fail} (red) for the two rockfall scenarios in the translational velocity - block volume plane. The blue line represents the Iso-Energy limit of 200 kJ

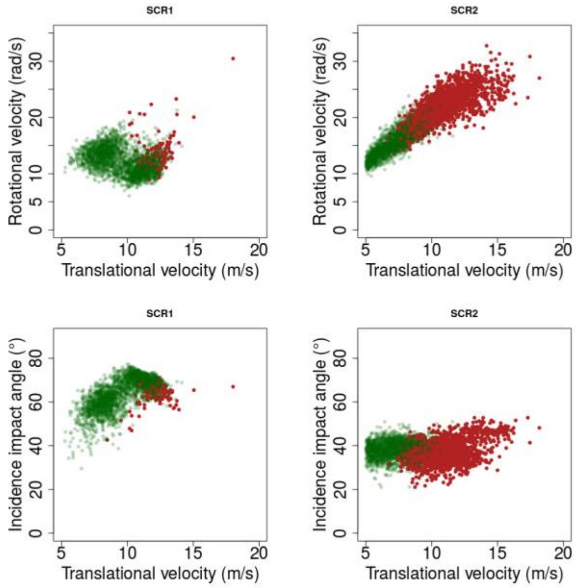

Fig. 8 Prediction of the B_{Succ} (green) and B_{Fail} (red) for the two rockfall scenarios in the translational velocity - rotational velocity plane and in the translational velocity - incident impact angle plane.

Fig. 8 and **9** show the influence of the rotational velocity, incidence impact angle, and impact position along the *X*-axis and *Y*-axis as function of the translational velocity for the two rockfall scenarios. For SCR1, the impact position along the *Y*-axis has a significant influence on the prediction. A higher number of barrier failures are associated to impact heights greater than 2 m. For SCR2 the impact position along the *X*-axis and the rotational velocity of the block show a significant influence on the prediction. The number of barrier failure increases for increasing impacts position along the *Y*-axis and for increasing rotational velocities.

On the whole, it appears that the real efficacy of a barrier in stopping the blocks strongly depends on the impact conditions related to the studied case and that the only translational kinetic energy may not be sufficient for estimating the ratio of stopped blocks.

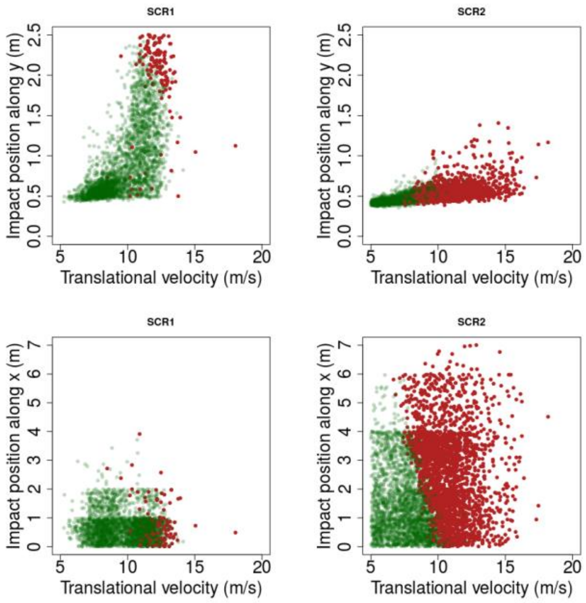

Fig. 9 Prediction of the B_{Succ} (green) and B_{Fail} (red) for the two rockfall scenarios in the translational velocity - impact position along *X* plane and in the translational velocity - impact position along *Y* plane.

4. DISCUSSION

4.1 Benefits of the meta-models

The current design practices are mainly based on the barrier reference capacity. In this study, the reference capacity of the barrier was considered as the reference value obtained from impacts following the recommendations of the European guideline ETAG 027 [*Eota*, 2013]. A straightforward design for this specific barrier would consider that all the block having a kinetic energy less than 200 kJ are stopped.

However, it was shown from FEM simulations that barrier failures occur below the 200 kJ limit. These behaviors appear to be dependent on the impact conditions. Analysis of the data also showed that, although some trends could be observed, there is no a simple correlation between input parameters and block-barrier interaction mechanisms. These results bring to light the shortcomings of deterministic barrier design approaches based on a single impact assessment test. This limitation can be accommodated by using probabilistic approaches to predict the barrier response as a function of the impact conditions.

A detailed analysis of the results presented in **Fig. 5** shows that the prediction of the meta-models below the the iso-kinetic energy line results in 4.8% of False Positive cases (critical cases associated to an overestimation of the barrier capacity) while considering the barrier reference capacity as a criterion led to a value of 52% (see **Fig. 3**). Restricting the comparison to a block size of 1 m (1/3 of the height of the barrier), leads to values of 4.5% for the meta-model compared to 40% for the barrier reference capacity based approach.

This means that the reference capacity of the barrier is far too optimistic with respect to the barrier ability in stopping the blocks. This demonstrates the benefit in using the meta-model for design or hazard assessment purpose.

4.2 Application to real sites

The assessment of the effectiveness of the barrier for two rockfall scenarios has brought to light the importance of the loading conditions on the barrier response. In scenario SCR1, impacts were rather centered on the barrier with high impact heights and impact angle ranging between 40 to 80° directed downward. In scenario SCR2, impacts were more spread to the edge of the barrier with low impact height and impact angle ranging between 20 to 50°.

Comparing the barrier reference capacity to the translational kinetic energy, the barrier may be considered efficient in stopping the block for the two rockfall scenario. This is confirmed by the meta-model results for SCR1, where only a limited number of block impacts (3% of the blocks) lead to barrier failure under the barrier reference capacity. On the contrary, the use of the meta-model to assess the barrier efficiency for SRC2 shows a substantial number of block impacts leading to barrier failure under the barrier reference capacity (42%). This high number of failure indicates the existence of critical loading conditions for this specific barrier type.

This last result shows the practical benefit in using the meta-model to evaluate the efficiency of the barrier by comparison with an approach based on the direct use of the barrier reference capacity.

5. CONCLUSION AND PERSPECTIVES

This article has proposed a method to assess the effectiveness of a cable net barrier through the development and the application of a meta-model.

The results of 280 FE simulations showed that the barrier efficiency to arrest the block depends not only on the block volume and its translational velocity but it is also controlled by other parameters related to the block trajectory. As a consequence, quantifying the barrier efficiency without accounting for their influence may lead to un-conservative estimates. For instance, 40% of the impact cases below the reference barrier capacity, as deduced from a normal-to-the-fence and centered impact, in fact leads to barrier failure in arresting the block.

A meta-model has been developed, based on the results of the 280 FE simulations concerning the ability of the barrier to arrest the block. The parameters ranges were defined considering the barrier reference capacity. The meta-models have been shown to provide an accurate prediction of the barrier response. In particular, the meta-model unconservative error associated to the ability of the barrier in arresting the block is less than 5%, compared to 40% following a straightforward design approach.

The meta-model was then coupled to a rockfall trajectory simulations tool to estimate the barrier effectiveness for two rockfall scenarios. This coupling approach allows accounting for the real distributions of the various parameters describing the possible block trajectories. It was shown that, depending on the scenarios studied the barrier effectiveness can be highly overestimated by using only the reference capacity of the barrier instead using the meta-model. The meta-model appears to be an important tool to assist practitioners and will represent a significant improvement in quantitative rockfall hazard assessment in presence of a protective barrier [*Corominas et al*., 2005].

It is worth highlighting that the considered impact conditions did not consider biased trajectories or rotational velocities around all block axes. This simplification is thought not to call into question the conclusions drawn and is assumed to be of negligible influence on the developed meta-models accuracy.

Finally, one perspective would be to use the meta-model developed to help in the optimization of the design of rockfall barriers, allowing for the identification of detrimental mechanisms leading to structure failure. In this case parameters related to the design of the structures may be considered, such as the position and initial tension of the cables, post spacing, position of energy dissipating device, if present. This does represent an inspiring perspective for manufacturers, designers and researchers.

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